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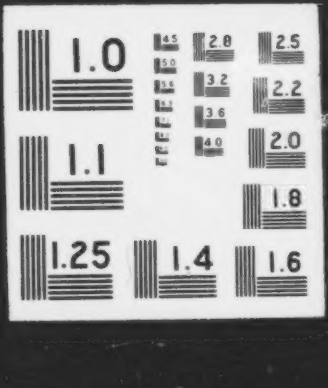
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AIR OVER CITIES: SYMPOSIUM HELD AT ROBERT A. TAFT SANITARY ENGINEERING CENTER, CINCINNATI, OHIO ON NOVEMBER 6-7, 1961

Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

November 1961

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ROBERT A. TAFT SANITARY ENGINEERING CENTER

284

Symposium

Air Over Cities

Sponsored by the
Laboratory of Engineering and
Physical Sciences
of the
Division of Air Pollution
U. S. Department of
Health, Education, and Welfare
Public Health Service
Robert A. Taft
Sanitary Engineering Center
Held November 6–7, 1961
Cincinnati, Ohio

Details of illustrations in this
document may be better studied
on microfiche.

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Introduction

ARTHUR C. STERN, *Chief, Laboratory of Engineering and Physical Sciences, Division of Air Pollution:*

My function here is to say welcome, but [illegible] have chosen instead to take the 10 minutes allotted to me to forecast what the role of the meteorologist, particularly the one in charge of a Weather Bureau station in a large metropolitan area, will be in the year 1985. This I hope may give you a little pattern for the talks to follow, and if you succeed in the following 2 days in setting all of the groundwork for this chore in 1985, we will have fulfilled our reason for getting together here.

Now, firstly, in 1985 the people will be more interested in whether the air is safe to breathe than whether it will rain. This, of course, will completely change many of the paramount functions in the normal operation of a Weather Bureau station.

During a typical day in the Weather Bureau station, the staff will not only study the classical weather maps at ground level and aloft, but also a recently developed (before 1985) basic horizontal plane air quality isoconcentration map. In addition to the latter horizontal plane maps, we will, of course, by then have a very well-developed set of vertical elevation data for a number of latitudes and longitudes, from the ground up to 5,000 feet. At particular stations, we will get from the facsimile elevation maps showing temperature, pressure, air movement, humidity, and air quality in the vertical plane. The station staff will choose the latitudes and longitudes that intersect the particular urban complex where their major interest lies, and also those proximate thereto. And although advisories will be sent from Washington -- I presume Washington will still be the capital of the United States then -- giving 72-hour, 48-hour, and 24-hour air quality forecasts, these forecasts will be routinely combined with the data obtained from the local vertical elevation maps and isoconcentration maps for air quality. The meteorologist will combine these with the daily source strength prediction, which he will receive each day from the local air pollution control agency; these two sets of data will be fed into the station electronic computer, which I am sure each of the stations by then will have.

To obtain these vertical elevation maps, we must have by 1985 a very well-developed national network for vertical sounding from the ground to 5,000 feet; this network will be as intense

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vertically as our horizontal network is now intense horizontally.

The electronic computer will develop local forecasts of air quality and the maximum source strength distribution that will keep pollutant emissions within air quality standard limits.

These latter data, that is the maximum source strength distributions, will simultaneously be typed out not only at the computer in the Weather Bureau station but also at the air pollution control headquarters, which will use them to provide quotas to various agencies.

I don't know whether by 1985 we can give hourly quotas, but certainly we will be giving quotas to the highway entrance control points as to the number of vehicles permitted to pass each hour, and to industrial sources for their hourly emission quotas. Also we will determine which portion of energy used in household and commercial enterprises is to be drawn hourly from energy storage reserves maintained for that purpose, and which portion may come from new energy conversion processes. Thus on bad days we will balance the ability of the atmosphere to handle the pollution with the amount that we throw into the atmosphere.

About at this point the computer will be hooked up to the telemetered local air quality monitoring network to make hourly comparisons between the predicted and the actual concentrations and to prepare hourly amendments to the source strength quotas.

Session 1: City Air – Better or Worse

H. E. LANDSBERG,* *Chairman*

Summary

Human activity has caused considerable changes in local climates. These modifications in turn have affected the temperatures of the lowest layer of the atmosphere, the diurnal temperature range, the shape of the diurnal temperature curve, the local relative humidity, the local electric field, the patterns and amounts of precipitation, and the speed and direction of winds. These effects have probably only a minor influence upon human well-being. Other changes, however, have potentially harmful effects. The most radical effect has been on atmospheric suspensions and admixtures. None of these changes have been beneficial. The growth of nearly all urban areas and industrial complexes has outpaced the engineering and legal efforts to minimize the nuisance and the possible dangers of contamination. Already the ill winds from one settlement can influence the next town downwind. The day of planning in terms of single communities is over, and whole regional patterns now must be viewed together. Our knowledge of air quality and its effects on health is not yet adequate. In the interest of public hygiene, an intense effort in biometeorological and medical research is required.

Census figures show that an ever-increasing percentage of our citizens have become urbanites or, at least, suburbanites. Eighty-five percent of the 28-million increase in the U. S. population in the 1951-1960 decade occurred in the standard metropolitan areas (as designated by the U. S. Bureau of the Census in 1961). These cover only 9 percent of the area of the country. This concentration of population has given rise to many problems. As this trend continues, major problems in planning will arise. Clean water for the population has been of public concern for a long time, and it is time that we do something about the air in the metropolitan areas. The reasons for this are clear and need not be repeated. As in all planning, however, we need a quantitative basis -- and this is only beginning to emerge.

There is no gainsaying that the towns and the cities constitute a radical change from the natural environment. These dense settlements help in commerce and trade, in culture and services --and in a bygone age they were even useful in common defense. But what price do we pay for our gregariousness? Some might point to slums, others to the rise in crime, still others to traffic difficulties. As meteorologists we are particularly interested in the changes of the atmosphere in urban areas. These are of considerable magnitude and of concern to our health and well-being.

Just 300 years ago there was problably only one place in the world which found itself vis-a-vis a notable man-made climatic change: London, England. The chronicler of the day,

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*Director, Office of Climatology, U.S. Weather Bureau

John Evelyn, F. R. S. (1661), gave a classical account of it. He focused attention on the problem of smoke pollution, which he attributed to channel coal used in some early manufacturing processes. Since that day and age one metropolis after another has had to face the same difficulty from various causes.

In colonial America with its small towns, wide-open spaces, and good natural ventilation, about a century after Evelyn a traveler could still admire the clean air. Thus, on his trip to the New World in 1761, the Vicar of Greenwich, the Reverend Andrew Burnaby (1775), a neighbor of smoggy London, could still rave about New York: "It lies in a fine climate, and enjoys a very wholesome air." But a century after the American Revolution we find a much less sanguine appraisal. No less an authority than the medical correspondent of Godey's Lady Book (1873) stated that the air of cities was thoroughly polluted by organic dust, thought to be spores or germs. Our great-grandmothers were enjoined to scrupulous cleanliness and an unceasing war against dust lest contagious diseases would threaten their health and even their lives. A Mr. Spence in England and the Reverend Mr. Gibsone on this side of the Atlantic suggested that smoke be discharged into the sewers instead of being poured into the atmosphere (Harpers, 1872).

In the twentieth century the problem has become truly worldwide. It affects in a melancholic fasion us, our allies, the neutrals, and the Soviets alike. Urbanization and industrialization have been, and will remain, in the ascendance. Thus the problem has become a matter of concern even to the World Health Organization (1961). It is the central theme with which we want to grapple in this symposium.

In the scientific approach of our day we have a few small advantages over Evelyn. He had only his senses of sight and smell--admittedly formidable qualitative tools--to diagnose the difference between the natural state and the man-spoiled environment. Since Luke Howard published for the first time in 1818 his treatises on the climate of London, we have been trying to ascertain by quantitative measures the magnitude of the change. The result is truly startling. Not a single atmospheric element has remained unchanged in the urban areas. Although we have only a few sets of "before" and "after" measurements, there are a large number of running accounts and comparative values between cities and surroundings.

More comprehensive surveys in the literature (Kratzer, 1956; Landsberg, 1956) present a more-detailed documentation than I can give here. Kratzer's monograph cites 533 references up to 1955. We now accumulate pertinent papers on this subject at the rate of 100 every 5 years, excluding those which deal only with techniques and effects in the air pollution area.

Tables 1 and 2 illustrate the city effect in a gross way. Table 1 deals primarily with the general climatic elements (Landsberg, 1958), and Table 2 with atmospheric admixtures (Katz, 1961). Where base figures of undisturbed areas are available, the differences of the city air environment are stressed.

TABLE 1

CLIMATIC CHANGES PRODUCED BY CITIES

Element	Comparison with Rural Environs
Contaminants:	
dust particles	10 times more
sulfur dioxide	5 times more
carbon dioxide	10 times more
carbon monoxide	25 times more
Radiation:	
total on horizontal surface	15 to 20% less
ultraviolet, winter	30% less
ultraviolet, summer	5% less
Cloudiness:	
clouds	5 to 10% more
fog, winter	100% more
fog, summer	30% more
Precipitation:	
amounts	5 to 10% more
days with 0.2 in.	10% more
Temperature:	
annual mean	1 to 1.5°F more
winter minima	2 to 3°F more
Relative Humidity:	
annual mean	6% less
winter	2% less
summer	8% less
Wind Speed:	
annual mean	20 to 30% less
extreme gusts	10 to 20% less
calms	5 to 20% more

TABLE 2

CONCENTRATION OF SOME AIR POLLUTANTS IN THE ATMOSPHERE OF URBAN AREAS

Pollutant	Concentration, ppm
Carbon Dioxide	300 to 1000
Carbon Monoxide	1.0 to 200
Oxides of Nitrogen	0.01 to 1.0
Sulfur Dioxide	0.01 to 3.0
Aldehydes	0.01 to 1.0
Chlorides	0.00 to 0.3
Oxidants	0.00 to 0.8
Ammonia	0.00 to 0.21
Fluorides	0.00 to 0.08
Dust	5 to 100 million[a]

Also highly variable amounts of gross dust, micro-organisms and pollen.

[a] Dust concentration in particles per cubic foot.

This raises the following fundamental question: are there any undisturbed atmospheric conditions left in the mechanized areas of the world? The answer is probably "No," and we have to be satisfied with using the less-perturbed conditions in the rural zone near the city for our base values. These data give us an approximate picture of how much human activity has unwittingly altered the parameters of the lowest layer of the atmosphere.

Two major changes have been introduced by man. One is the radical alteration of the surface, the other is the continuous addition of a wide variety of substances -- gaseous, liquid, and solid -- to the air. It is not entirely possible to separate the effects of these alterations; however, some of them can be stated in general terms.

The change of surface involves particularly the radiation balance. In some locations a new effective surface is created; run-off and evaporation character of the surface is sweepingly altered. The air motion is basically affected by changes in the roughness parameters. On a microscale, wind channeling occurs. Thus, we see that even a city without heating devices, industry, or motorized traffic would create a climate different from that of the surroundings. A mental picture can be made by imagining the replacement of fields, forests, streams, and ponds by a barren rock formation with deep canyon-like cuts.

The other change is even more complex. The simplest phase involves the addition of heat from local sources, ranging from the metabolism of the inhabitants to domestic and industrial heating processes. Substantial amounts of water vapor also are added from combustion processes, and by steam releases from power plants, laundries, and other industrial establishments. The gamut of chemicals injected into the atmosphere is yet to be listed anywhere. From a meteorological point of view dust particles in the sub-micron and micron ranges, carbon dioxide, and a few hygroscopic substances are probably most important. From the aspect of health and hygiene many more substances could be cited. Perhaps carbon monoxide, sulfur dioxide, some aldehydes, and fluorine compounds should be singled out because of their immediate noxious effects.

Here might be a good point to digress. Although a great deal has been learned about the special climatic characteristics of cities, progress has been hampered for two reasons:

1. Too little information is available on a strictly comparative basis from series of observations in the city and in rural proximity. Generally, such parallel series are available by accident rather than by design. This is the case for the usually observed weather elements at a city station and an outlying airport. These intercomparisons are often complicated by the fact that airports are located in selected microclimates and at considerable distances. Lacking particularly are simultaneous observations of the radiation balance and of the vertical wind structure in the lowest 1000 feet.

2. The second point covers the special orographic and geographic peculiarities of various locales. With some luck we might contrive to arrive at an abstraction of a city climate per se, in contrast to a forest climate or a mountain climate or an island climate or other types of mesoclimates. For practical purposes, however, this will accomplish little. In addition each city climate must be studied for its own peculiarities. This is particularly essential since many settlements are in a specific locality because of some "favorable" geographical features, such as a river, a lake, a natural harbor, a plain in front of a mountain range, or a valley system. All these features introduce microclimatic variants that couple with the city influences to create special combinations. Even the macroclimatic setting is of importance. The problems of Southern California are a striking example.

In addition to the broad general studies of city climates, therefore, we need detailed analyses of each locality. In a modern dynamic approach only a bare start has been made. The classical studies of Besson (1931) placed the problem in the right framework of scientific inquiry and recent publications such as those on Vienna (Steinhauser et al. 1955, 1957, 1959) have shown most exhaustively what can be done. In this country we have considerable information on the Los Angeles Basin by many contributors. (Only a few are cited here: Edinger, 1958; Edinger and Helvey, 1961; Neiburger, 1955a, 1955b; Haagen-Smit, 1958; Frenkiel, 1957.) Even these fine studies remain fragmented reports and papers. And what about the other 74 standard metropolitan areas? There exist only a few scattered studies on their atmospheric environment. Private enterprise, the planners of the future, and even the intelligent citizen-voters need authoritative and comprehensive reference sources on the mesoclimate of the metropolitan areas; these, however, remain to be written.

In returning to the main theme, I would like to cover some of the principal alterations in climate caused by cities. Much of this will illustrate points already made. In view of the system employed by past studies, it is easiest to proceed by meteorological elements.

There is some information -- if rather limited -- on radiation conditions. The gist is that the city environment, particularly smoke, reduces the total duration of sunshine and the intensity of solar radiation. The latter is particularly notable in the short wave lengths.

This is easily demonstrated for illumination. The city generally is darker than the environs. A survey in the industrial section of Zaporozhe in the Ukraine, a center for the production of steel and other metals in the Dnieper Valley, showed this well (Fedorov, 1958). There the midday diffuse illumination was reduced by about 5 percent in May and June and by 21 percent in December, with an average annual reduction of 13 percent.

There is need for a great deal more information on comparative values of spectral intensity of solar radiation at the earth's surface inside and outside the city atmosphere. This is the more desirable because of the bactericidal action of ultraviolet radiation below 3000 A. Even in polluted city air there is still some residual killing action of solar radiation on microbes, as experiments in Leningrad (Krupins et al., 1954) demonstrated. We know very little about conditions across a metropolitan area, based on standardized micro-organisms and simultaneous spectral pyrheliometer observations. We do not even know with certainty that some of the pollution products did not kill the microbes used in the experiments carried on so far.

Locally, the absorption of radiation by the polluted city air might have fairly profound influences on the temperature of the absorbing layer. In England recent measurements in the infrared from aircraft have shown that in extreme cases this effect may account for temperature rises of as much as 5°C (Roach, 1961). The magnitude of the attenuations is shown in Table 3.

TABLE 3

COMPONENTS OF ATTENUATION IN LOWEST 1,000 FEET OF THE ATMOSPHERE[a]

	Visible λ, %	Infra-red λ, %	Total λ, %
Absorption	5	35	20
Back-scattering	5	5	5
Forward-scattering	90	60	75
Total	100	100	100

[a] After W. T. Roach

The conviction of the author is that the absorption effects contribute in reality only in a minor way to the temperature rises that have been observed in cities. These have been documented for many locations, ever since Luke Howard's early effort. With all the orographic varieties that are found in city locations, the "heat island" effect is well demonstrated. One of the most thorough recent studies in a not-too-complicated setting is that of Sundberg for Uppsala (1950, 1951). Mitchell (1953) has shown that population increases account reasonably well for some of the secular changes observed in metropolitan areas.

As for many other micro- and mesoclimatic effects, city influence becomes most obvious on clear days and nights. (It is, of course, always there.) An interesting effect is notable in the diurnal variation of temperature. In the hours after sunrise, city and country show little difference; by and large, the maxima are not too different. But in the late afternoon the differences begin to show. In the country cooling with setting sun is rapid. Outgoing radiation is unimpeded. Grass and soil lose their heat by radiation rapidly; little heat is supplied from deeper layers. In the city, pavements and house walls absorb a lot of heat during the hours of high sun. After sunset they begin to radiate toward each other instead of against the sky. They are better heat conductors than open land with vegetation. Hence they can draw on conducted heat from lower layers. Direct heat sources are also involved (furnaces etc.). Their effect is greatest during the cool hours of the day. All this combines into a slower decline of temperature in the evening, higher temperatures at night, and notably higher minima. This is demonstrated by frequency distributions of country-city temperature differences for the daily extremes. In the simplest orographic settings there is little difference in the daily maxima; the differences are almost normally distributed. In the minima, however, the distribution is notably skewed. Both in summer and in winter there is a high preponderance of excess temperatures in the city, with the largest departures noted in winter.

The larger the city, the more pronounced the effect between center and outskirts becomes. The complications that arise are often the effect of microclimatic settings. These are particularly notable in the warm season when land, lake, or sea breezes and mountain and valley breezes attain their greatest extent. The literature contains some exceptional examples of contrasts in temperature between a city and its surroundings. In many cases only a fraction of the observed temperature contrast can be ascribed to city influence (Duckworth and Sandberg, 1954).

There are, however, some beneficial effects of the nightly temperature excess in the city. It reduces the heating degree-day values and hence the fuel requirements. A comparison of 13 pairs of city-versus-airport station records in the Weather Bureau network shows an average of 10 percent reduction in degree-days between the two locations. Baltimore is a typical case. The mean annual value of degree-days at the Friendship International Airport is 4787 but only 4203 in the downtown district. For a completely fair picture one should also present comparative data for cooling degree-days in summer, but, unfortunately, no series of such observations has as yet been worked up.

A direct effect of the slightly warmer city climate is a reduction in seasonal snowfall. This has recently been shown for Montreal and Toronto (Potter, 1961). In Toronto, which has a seasonal total of 60 inches, a decrease of about 2 inches can be ascribed to city effect.

In a number of cities the increased minima lead to an earlier cessation of freezes in spring and later initiation of the freezing season in autumn. The values are quite variable according to the microclimatic settings, but differences of a week on either end of the freeze-free season apply to many cities.

Meteorologically most intriguing is the behavior of precipitation over city areas. It is of interest in the air pollution problem because of the substantial wash-out effects of precipitation. These are generally beneficial, except for the presence of fission products from weapons tests. It should be stated at the outset that the influences of the city on precipitation are most complex and the various skeins are not easily unraveled. We can say with reasonable confidence, however, that most of them tend to increase precipitation. These causes are enumerated without emphasis on the order: water vapor addition from combustion processes and factories; thermal updrafts from local heating; updrafts from increased friction turbulence; added nuclei of condensation leading more readily to cloud formation; and added nuclei which might possibly act as freezing centers for subcooled cloud particles.

Only a few pieces of evidence are cited here. The case of the gradual increase of rainfall over Tulsa, Oklahoma, with its growth from a village to a city in 5 decades, is presented with diffidence. The fact that current rainfall comparisons between city and airport station still show about an 8 percent difference lends some support to the hypothesis that in this orographically uninfluenced area the city really has led to the precipitation increase. The winter values are relatively higher; this is also favorable to the hypothesis of city influence because shower conditions in summer are not likely to be too much affected.

The excess production of condensation nuclei over the city is a long-established fact (Landsberg, 1938) and has been reaffirmed with many amplifying circumstances (Georgii, 1959). We do not yet have complete evidence for the freezing nuclei, although measurements in the Washington, D. C., area suggest that for the low-temperature end there is a considerable surplus in the metropolitan area (Kline and Brier, 1961). There is even a suggestion that giant nuclei, which may initiate the coalescence process, are more abundant in an industrial area than elsewhere (Semonin and Stouk, 1961).

We can hardly escape the conclusion that a pollution effect is at work when a weekly cycle is shown to be operative in industrial areas. This was first suggested by Ashworth (1929) in England's industrial area. Frederick recently (1961) made a new analysis of this phenomenon in the United States. He showed a definite minimum of Sunday rainfall for a 10-year period at Louisville, Pittsburgh, and Buffalo. These cities had fewer total days with precipitation on Sundays than on weekdays and the least average amounts for rainy Sundays compared to rainy weekdays. This study is still incomplete but is certainly suggestive. The possibility of "seeding" over metropolitan areas is strongly suspected in a snowfall case reported (v. Kienle, 1952) for Mannheim, Germany, and might well have been the case for a rather remarkable snowfall in Leicestershire, England (Murray, 1957). A strong city influence is also suggested in the snow patterns published (Potter, 1961) for Toronto, Ontario. Here, as in other cities, mesoclimatic influences such as Lake Ontario may play a role. Such influences may not be entirely lacking in the rainfall patterns over Chicago, although an urban effect on rainfall there seems to be present almost without doubt. The study by Chagnon (1961) estimates this effect accounts for 2.3 inches of an annual total around 35 inches.

In the smaller town of Champaign-Urbana, Illinois, Huff and Chagnon (1960) found no higher frequency of excessive rainfalls, of practical importance, than in the surroundings. Their study is a reminder of an earlier, almost unknown dissertation by Belger (1940), who investigated some frontal storms over Berlin, Germany. He studied only four cases in detail but in two found very marked increases in rain intensity over the metropolis; a similar case has been discussed by Hull (1957) for Washington, D. C. More important, perhaps, is Belger's rather remarkable finding that in all the Berlin cases a notable retardation of the squall lines or rain fronts over the city took place.

This brings us to the consideration of an important question: what influence does a city exercise on the circulation? We do know that the wind speed is considerably reduced in the built-up area. This is a simple consequence of increased friction. There have been suggestions from time to time that with weak gradient winds the city is capable of setting up its own circulation. The late Professor Berg in Cologna (1959) tried to obtain evidence for a city and country breeze system. He concluded that a general wind of 1 to 2 meters per second is sufficient to suppress the nightly country breeze, which otherwise can be set up by the 3^o to 3.5^oC temperature difference between the city and the country. I know of only one well-documented case of complete convergence of wind from all sides into the city. This was based on rime deposits in the Japanese city of Asahikawa (Okita, 1960).

With the help of data from meteorologically instrumented towers we are beginning to get a feel for the temperature field in the vertical over a city area, as shown by the studies of DeMarrais (1961) for Louisville and earlier by Duckworth and Sandberg (1954) for San Francisco. These studies indicate that the city undoubtedly superimposes a wind field of its own upon the general flow pattern. Observations of slow pilot balloons and floating balloons, used over some west coast cities, have given similar indications. Nevertheless it is almost impossible with the material now available to disentangle land and sea breeze or mountain and valley breeze from the city and country breeze. Investigations in much simpler orographic settings are needed.

From a practical point of view the general flow patterns and dynamic conditions in the atmosphere are probably more important. These will be discussed later. Here may be a good place to insert information on the material human activities add to the air of our cities. These cover probably the whole range of chemical substances used in modern civilization and all the by-products produced incidentally in their manufacture. In addition, there are all the intermediate and end products of combustion processes, not the least of which are those of internal combustion engines of motor vehicles.

Much of the material is in solid form, ranging from submicron particles to flyash in the millimeter sizes. The larger particles fall out by gravity and generally stay in the urban or suburban areas. In the modern metropolitan districts this dust amounts to 100 tons per square mile per month. It is likely to be more a nuisance than a menace. McDonald (1961) recently estimated the mean residence time of this material at a few hours only. It must be assumed that the smaller particles stay suspended for a much longer time (Hess, 1959). The largest fraction appears to be in the micron size. This material without doubt penetrates into the upper respiratory passages and, according to its composition, might readily serve as an irritant. There is also persistent evidence that the number of microbial organisms shows a high correlation to the number of suspended particles. Although it is not proven, there is a suspicion that some of these organisms attach themselves to the suspensions. The influence of the suspensions on the electric properties of the atmosphere are well known (Beckett, 1958; Mühleisen, 1959). Whether or not this has health effects remains to be explored (Reiter, 1960).

There is a better estimate on the effects of the gaseous admixtures. Only O_3, CO, CO_2, and SO_2 are mentioned here. The oxidants usually represented by ozone have been most widely discussed (Neiburger, 1959); they are by no means restricted to Southern California, (see e. g., Wanta et al., 1961). These oxidants show definite adverse effects on both crop plants and humans. Much less demonstrated is the influence of CO. This insidious compound is present in appreciable quantities in the traffic-clogged canyon streets of our cities. A survey in Hamburg, Germany, revealed some remarkable consequences (Effenberger, 1957) of carbon monoxide in city air. Suburban residents showed 1. 56 percent carboxyhemoglobin in blood samples; those living in city apartments 1. 82 percent and traffic policemen as much as 9. 5 percent. We may wonder how many headaches can be attributed to this pollutant. Under inversion conditions with calm, concentrations of 0. 005 volume percent of CO were found; this is decidedly high value for a gas that shows such deadly affinity for our blood.

The production of CO_2 by combustion processes is another source of urban and industrial air pollution. As far as health effects go, it probably can be dismissed, even though it may increase by 10 percent over the normal in polluted city air. An example of this is shown in the difference between December and April mean values by Steinhauser (1959) for Vienna. Much has been written about the possible influence of CO_2 concentration upon heat absorption in the atmosphere. Some have adduced it as the cause of rising temperatures of the earth (Callendar, 1961), and although this is only a hypothesis at present, the matter deserves close watch in the future.

SO_2 is probably another pollution product (Weiss and Frenzel, 1956; Lenshin, 1958). There is good evidence, for example that SO_2 increased markedly in the fatal London smog of December 1952. Russian workers (Bushtuveva, 1954) have shown that such increases in SO_2 are related linearly to simultaneous presence and increases in H_2SO_4. These irritants are likely to be among those causing the well-known symptoms of air pollution afflictions.

At present we can only wonder how much city air contributes to general morbidity. It is certainly a problem that requires more detailed attention than it has been given heretofore (Heimann, 1961). Offhand it appears that the city influence would be more pronounced on respiratory diseases than on diseases affecting any other system of the organism. Just contemplate this formidable list: asthma, bronchitis, bronchiectasis, common cold, diptheria, emphysema, the influenzas, the pneumonias, laryngitis, phthisis, pleurisy, tuberculosis, and whooping cough. Although many of these are caused by specific microorganisms, others are simply symptom-complexes possibly due to chemical irritations, which in many cases are followed by infections (Babayants, 1949). Respiratory complications are often the cause of death in the elderly afflicted with cardiac and circulatory ailments. Although, except for episodes of the Donora type, these relations cannot readily be discovered (Hechter and Goldsmith, 1961), the subjective complaints should not be overlooked. In a recent survey, for example, residents in the Los Angeles area, showed a much higher incidence of malaise attributed to air pollution than other inhabitants of California (Table 4) (Breslow, 1961). Although psychological factors might have inflated these figures, they cannot be completely dismissed.

In spite of the many contributing local micrometeorological factors, the general meteorological pattern of air pollution is simple. There is essentially only one factor that causes accumulation of waste products — lack of ventilation. Two elements contribute to this: (1) vertical stability or low-level inversions that prevent vertical motions and turbulence and (2) calms and slight wind motion. From general climatological observations and the upper air records a picture of the air pollution potential of various

TABLE 4

AIR POLLUTION EFFECTS REPORTED BY CALIFORNIA RESIDENTS[a]

(Percent of people surveyed who registered complaints in Los Angeles County compared with those in remainder of State.)

Ailment	Excess % Cases
Eye complaints	22
Nose complaints	21
Asthma	17
Throat complaints	16
Hay fever	13
Shortness of breath	11
Coughing	10
Bad headaches	10

[a] From Breslow (1961?).

localities or broad geographical regions can be gained. The most recent publications in this field are by Dickson (1961), Boettger (1961), and Hosler (1961). These studies show that vast areas of the United States have these two meteorological prerequisites for temporary air pollution accumulations. Fortunately, the self-cleansing mechanisms of the atmosphere are also at work. Gravity helps in promoting fallout; basically, however, strong wind and washout by rain are the effective agents of pollution dispersal and dilution. Frequent precipitation and winds above 10 miles per hour can be counted upon in many of our industrialized regions to hold air pollution to proportions which do not lead to acutely dangerous episodes. In spite of the remarkable natural dissipation system of pollutants, however, constant vigilance through continuous surveillance is important.

A major problem of the future is large-area pollution. Area-wide difficulties have existed for some time in England's Midlands and in the German Ruhr region. In the United States as population primarily in metropolitan areas increases, towns grow into cities, and cities into metropolises. With sprawling suburban areas and industrialization along belt highways, separate urban entities grow together and form a conurbation which some have dubbed a megalopolis. Under these circumstances the pollution spread is no longer a mathematically neat problem of a point source influenced by diffusion and turbulence. Only under specialized conditions, such as atomic plant operation, is this still an acute problem. We do, however, have to face the fact that there are already innumerable single pollution sources in various nuclei over large areas -- and in the not-too-distant future in long chains of cities.

One of these sources will be the city system from Richmond, Virginia, to Portland, Maine. This stretched-out chain of settlements, industries, and traffic soon will have to be studied as a single entity. As an example the author tried a very rudimentary approach as a crude first approximation. Since January 1961 the Weather Bureau has been publishing regularly the daily wind resultant for all major stations, based on the 24 hourly observations

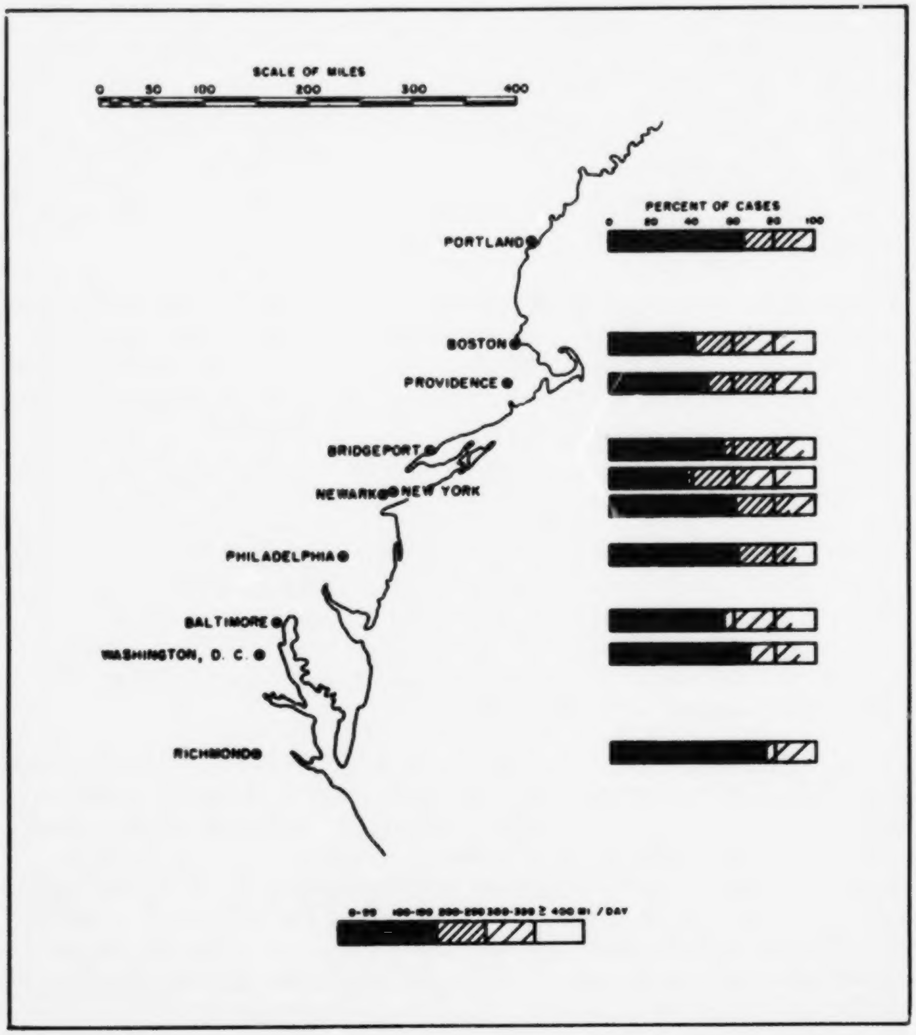
SCALE OF MILES
0 50 100 200 300 400
PERCENT OF CASES
0 20 40 60 80 100
PORTLAND
BOSTON
PROVIDENCE
BRIDGEPORT
NEWARK
NEW YORK
PHILADELPHIA
BALTIMORE
WASHINGTON, D. C.
RICHMOND
0-99 100-199 200-299 300-399 ≥ 400 MI /DAY

Figure 1. Daily wind motion, from 24-hourly wind resultant, along the densely settled NE coastal sector of the U. S. for first 8 months of 1961. Black area in frequency diagram at right shows cases when air motion is slight and pollution products are apt to stay within settled area.

during the day. The resultant gives a quick, if not too accurate, idea of the air transport during the day. Figure 1 shows a breakdown by resultant distances of wind movement, for the first 8 months of 1961, for the following sequence of 10 cities: Richmond, Va., Washington, D. C., Baltimore, Md., Philadelphia, Pa., Newark, N. J., New York (La Guardia Field), Bridgeport, Conn., Providence, R. I., Boston, Mass., Portland, Me. Airport winds can be taken as fairly representative for a city in general, as shown in a study of Nashville by Frederick (1961).

A considerable number of days showed less than 100 miles air transport per day. This means that with suitable wind direction pollution products will stay in the general districts of which these cities are centers. As might be expected from the general meteorological pattern of the area, the southern part of the chain shows the greater number of slow transports. On the other hand the 8-month sample, which includes data for winter and spring, shows a fair percentage of movements over 300 miles per day. These can be considered as a cleansing influence in the area. Data for autumn will undoubtedly boost the share of the weak winds, but these were not available when this was written.

Typical situations at the extremes of this distribution are shown in Figures 2 and 3. Figure 2 shows generally slow winds along the chain of cities on June 12, 1961. The very weak pressure field of the synoptic situation is a primary indication. Under such circumstances pollution products can be expected to stay in the local area or to be wafted slowly toward the next city in the chain. If visibility is used as a primitive index of pollution, very low minima are noted. Such weather conditions, at least for parts of the chain, are not exceptionally rare.

A converse case is shown in Figure 3. This occurred on February 9, 1961, when an offshore low-pressure system with a tight pressure gradient caused the resultant winds all along the chain to be at right angles to the conurbation. Pollution products cannot accumulate under these circumstances and would be blown far out to sea. Even the lowest visibilities of the day were good.

Obviously, these cases should be studied with more refined analyses, but this primitive approach gives an idea of future problems.

Are there other problems that should receive more attention? In the author's opinion, in our study of the basic problems of city climate, we have neglected those man-made factors which can lead to improvements (Katz, 1956). Most of these are of a microclimatic nature. In the old days it was generally considered adequate to place smoke sources in the lee of the city according to the generally prevailing wind direction; it would be more

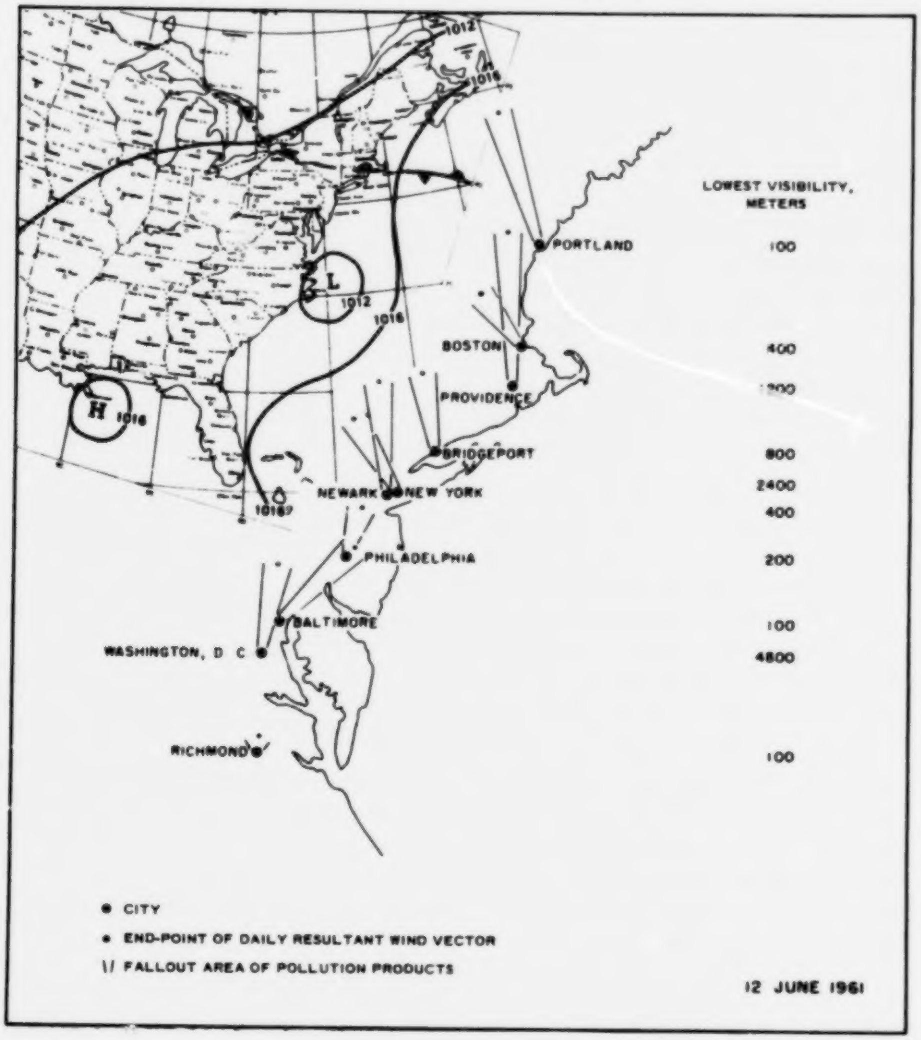
1012
1016
1012
1016
L
H
1016
1016?
LOWEST VISIBILITY, METERS
PORTLAND
100
BOSTON
400
PROVIDENCE
1200
BRIDGEPORT
800
NEWARK
NEW YORK
2400
400
PHILADELPHIA
200
BALTIMORE
100
WASHINGTON, D C
4800
RICHMOND
100
● CITY
• END-POINT OF DAILY RESULTANT WIND VECTOR
\/ FALLOUT AREA OF POLLUTION PRODUCTS
12 JUNE 1961

Figure 2. A case of weak winds. Upper left inset shows pressure distribution at 0100 EST. Figures at right show lowest visibilities during 24 hours of 12 June 1961.

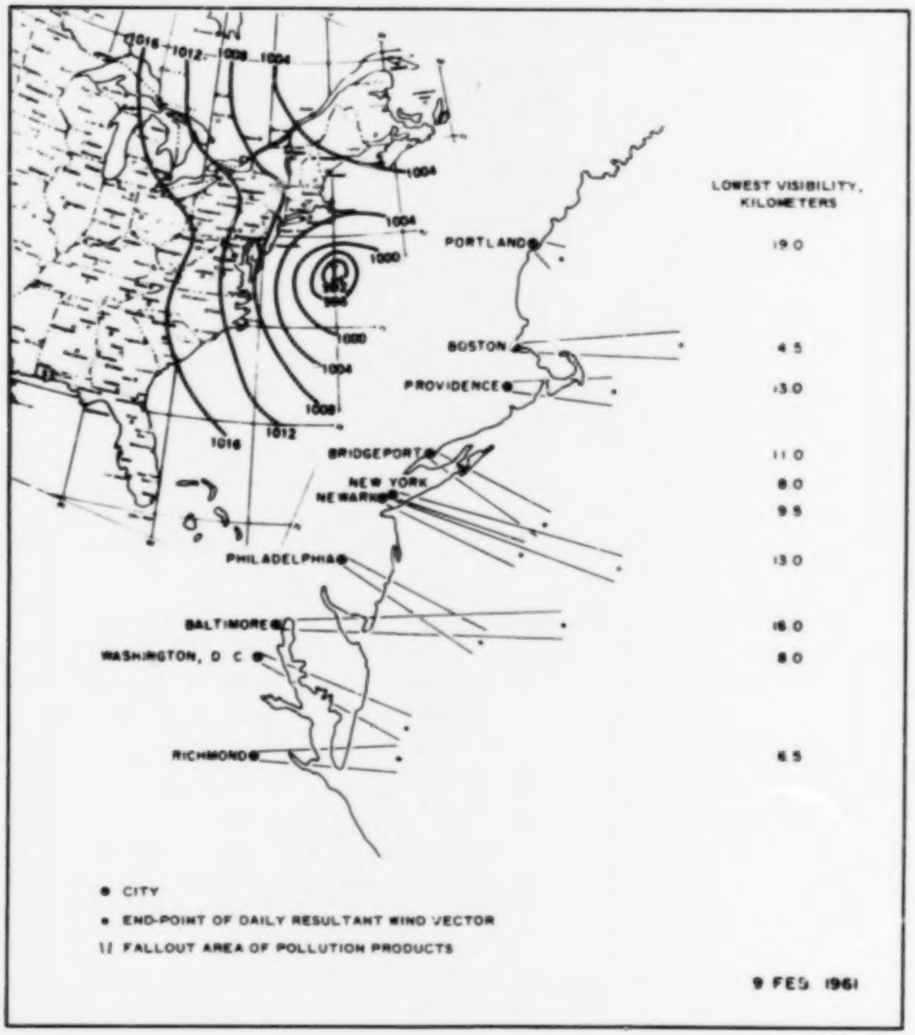
1016
1012
1008
1004
1000
992
996
LOWEST VISIBILITY, KILOMETERS
PORTLAND 19.0
BOSTON 4.5
PROVIDENCE 13.0
BRIDGEPORT 11.0
NEW YORK 8.0
NEWARK 9.5
PHILADELPHIA 13.0
BALTIMORE 16.0
WASHINGTON, D. C. 8.0
RICHMOND 6.5
● CITY
• END-POINT OF DAILY RESULTANT WIND VECTOR
\/ FALLOUT AREA OF POLLUTION PRODUCTS
9 FEB 1961

Figure 3. A case of strong winds. In this type of situation pollution products are apt to be dissipated to sea.

appropriate to substitute the direction prevailing for the slight winds under inversion conditions. Local air drainage problems also should be given greater consideration.

Among the positive measures are the creation of open spaces and parklands, avoidance of solid walls of buildings, and construction of buildings of irregular heights. All of these counteract the blocking of winds. For the gross dust, shrubbery, trees and hedges have proven to be good filters and could be used to much greater extent.

In industrial areas the truly noxious substances must be suppressed to a much greater extent. This will require further research to distinguish between these and the effluents which are harmless to health. Even now the question might be asked: why permit any SO_2 emission at all? There are other culprits equally well known. Perhaps the idea of a smoke sewer is not as completely harebrained as it sounds. In fact it has been in use for years in Europe in connection with some smelters. Certainly smokestacks on mountain and hill tops will reach over many a low-level inversion and into the layers of higher wind speeds. The ratio of cost to benefit is not easily worked out for such an installation on a large scale, but it certainly deserves a most serious engineering study with a realistic assessment of the public health benefits.

Cars are likely to remain a major difficulty for many decades to come. It is too much to hope for complete electrification of surface transportation, but more of it may come in the metropolitan areas before they choke completely in traffic tangles and exhaust fumes. In connection with the latter the automotive industry certainly can use more inventors.

For decades safe drinking water has been a basic right. The body needs only a few liters of water each day, whereas, the body at rest needs 12,000 liters of air in a day and at work twice as much. At this rate we strain or pass through 10^{12} particles per day. A contaminant that is present at only one part in a million moves through the system at the rate of 12 to 20 cubic centimeters in a day. For many of these substances we would shudder to think of getting that much in a single dose. If we get it diluted we live in the hope that it is harmless. Is it too much to expect clean air, as we have come to expect clean water?

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Air Pollution Studies in the Netherlands

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Summary

A study is made of the increase in concentration of atmospheric pollution at the earth's surface in large cities and industrial areas when stability increases. By means of some simplifying assumptions, it is shown theoretically that when stability increases discontinuously the increase in concentration of pollution initially is proportional to time and for extended periods of stability is proportional to the square root of the time. A linear increase of concentration with time is also found with a slow increase of stability. The theory is illustrated numerically by data from measurements obtained in three case studies. The empirical data are reasonably well represented by theoretical formulas.

Air pollution began to be felt as a problem in the Netherlands almost immediately after the second World War, when the industrialization of the country progressed rapidly. Its harmful effects, even in a flat and windy country like the Netherlands, were experienced for the first time in an area northeast of big steelworks to the west of Amsterdam when severe damage was done to flower estates. Figure 1 shows the total damage observed at the end of summer, expressed in a relative measure; the Sutton pattern can be recognized clearly. The curves are less flat than they should be according to theory, because the wind direction was, of course, not constant during the whole season. The problem has been solved, more or less, since the steelworks built a 150-meter chimney.

At the same time the ever-increasing industrialization in and around the second largest harbour of the world, (New York being the largest) Rotterdam, just to the south of one of the most important horticultural districts of the country, became more and more a nuisance. In this case we could not attribute any damage to one special industry but had to consider the integrated effect of a large number of sources at various heights; this led us automatically to a study of the problems that are specific for the topic of this symposium.

We considered several aspects of the behaviour of pollution in such an area; special attention has been given to the role of atmospheric stability in some cases. Three examples are given in this paper and are illustrated with some figures.

First we tried to get an idea of what happens to concentra-

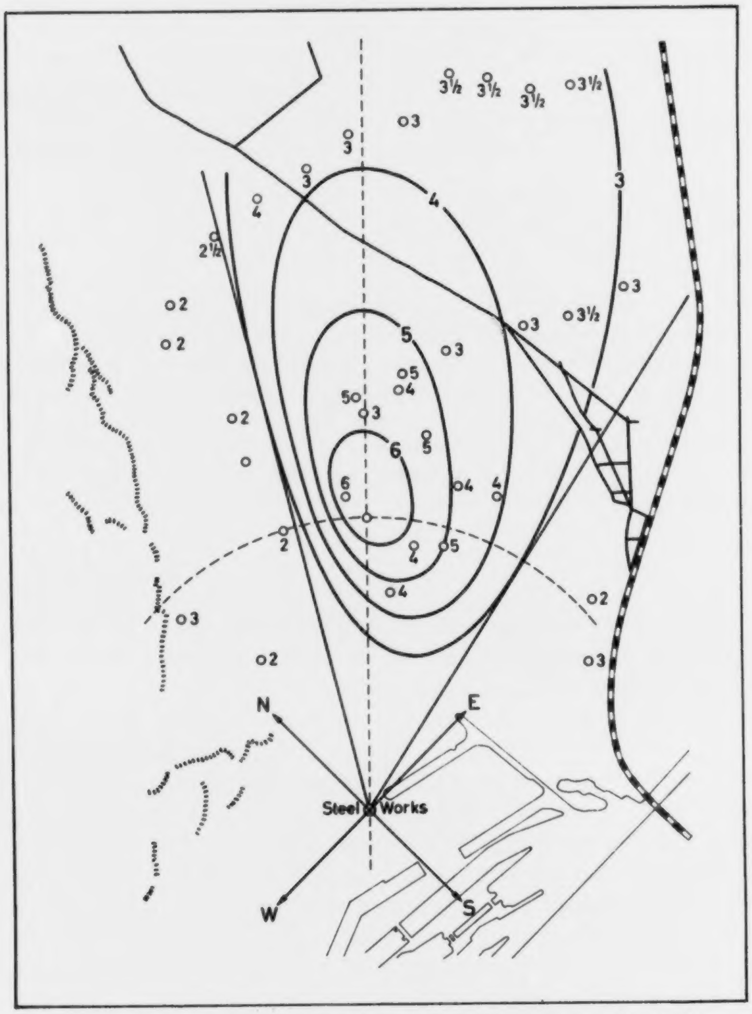

Figure 1. Patterns of pollutant damage to vegetation near Amsterdam.

tions in an urban area when stability in that area increases suddenly. In such cases, at least in the dangerous ones, there is generally little or no wind and the pollution balance is almost exclusively governed by the production of pollution and its upward transportation by turbulence.

Assuming equilibrium during the period preceding the stability increase, including the effect of advection into the vertical transport, which is of course physically not correct, and taking an area so large and homogeneously contaminated that the variations of concentration in horizontal directions may be ignored, another relatively rough approximation, we get equations that can be solved by Laplace transform (see Bouman and Schmidt, 1961). We are interested in the variation of ground concentration with time after the moment stability increases suddenly. The result is that after a short period, during which only the sources in ground level - automobiles for example - add to the ground concentration, all sources start to increase, resulting in an increase of that concentration proportional with the square root of time.

The result has been tested successfully in a number of cases. Figure 2 shows as an example the SO_2 measurements made in the centre of London during the great smog of December 1952. The theory provides a possibility within certain limits to forecast to what level concentrations may rise under such circumstances.

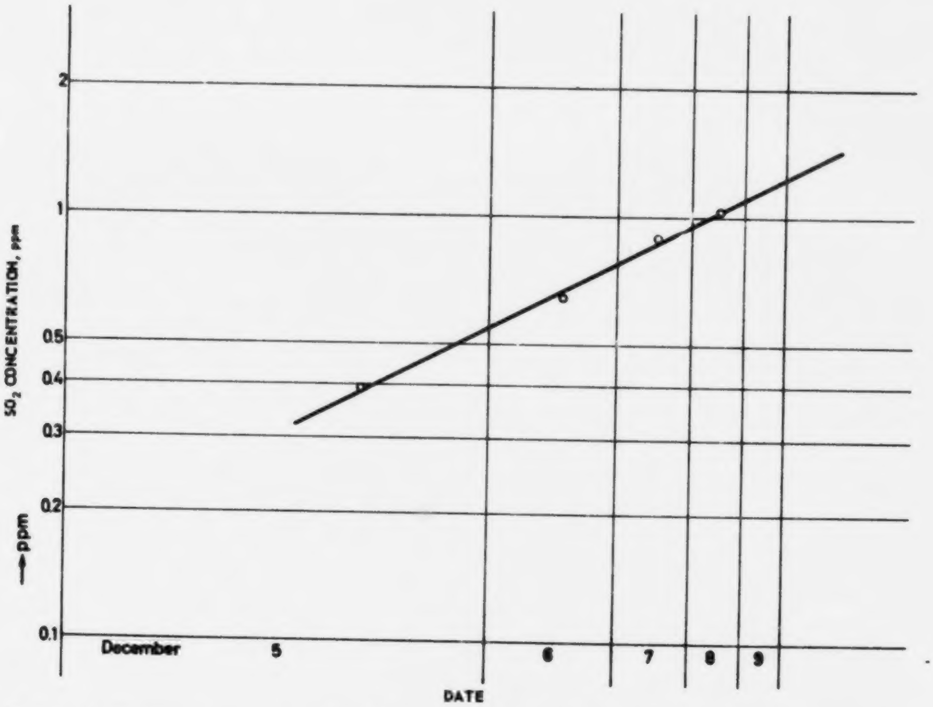

Figure 2. Measured concentrations of SO_2 in London during smog episode, December 1952.

Secondly the hourly observations of the dust content of the air, made in the centre of Rotterdam and measured by the well-known filter method, have been analysed harmonically. Generally, the dust content over the day, averaged for instance for every month of the year, is such that we find the curve reaches a pronounced maximum in the morning and more or less flattens for the rest of the day. It may be assumed, therefore, that it is especially the morning part of the curve that determines the harmonic components. It is found that the first harmonic generally has the largest amplitude of all.

If stability plays a role in the daily variation of the dust content of the air, its influence may be assumed to appear especially in the first harmonic. If the morning observations are assumed the most important ones, therefore, through the year we may expect a shift of the time at which the first harmonic shows its maximum.

Figure 3 shows the time of sunrise and the times at which the first harmonic and the combination of the second and the third harmonics obtain maximum values. It seems that the part of the morning maximum that is due to stability occurs about 1 hour after sunrise.

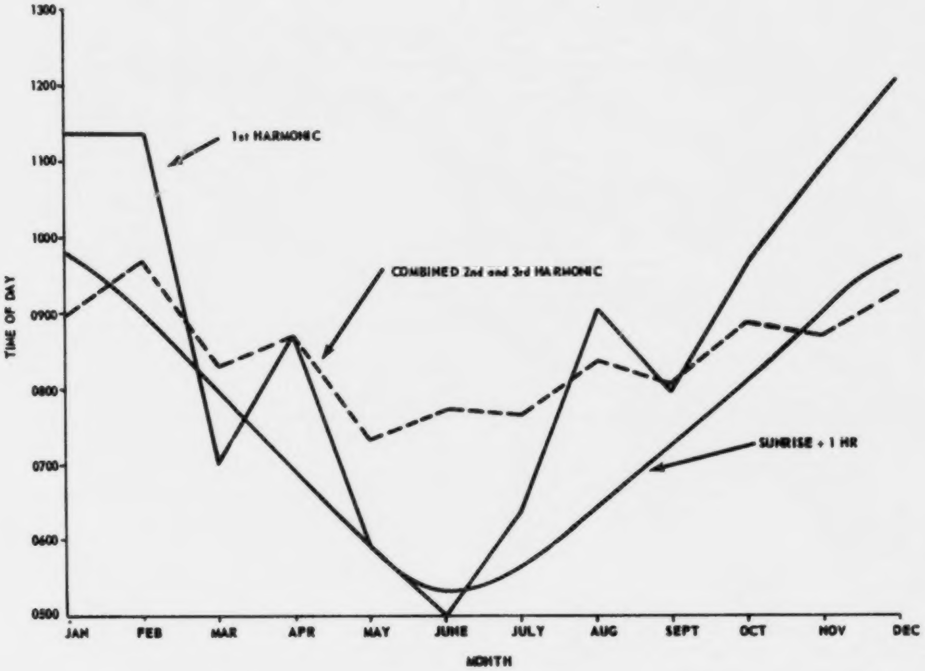

Figure 3. Harmonic component patterns based on hourly dustfall observations in Rotterdam.

Finally, if the first harmonic depends mainly on stability, its relative amplitude, i.e., its contribution to the total morning maximum, may be assumed to depend on cloudiness. High values of cloudiness result in small variations in stability, and vice versa. This is even more true with respect to precipitation. Apart from its direct connection with cloudiness, precipitation wets the earth's surface and thereby reduces the daily variation in stability. In Figure 4 the total monthly amount of precipitation is plotted against the amplitude of the first harmonic over the total morning amplitude; the effect of precipitation can be observed clearly.

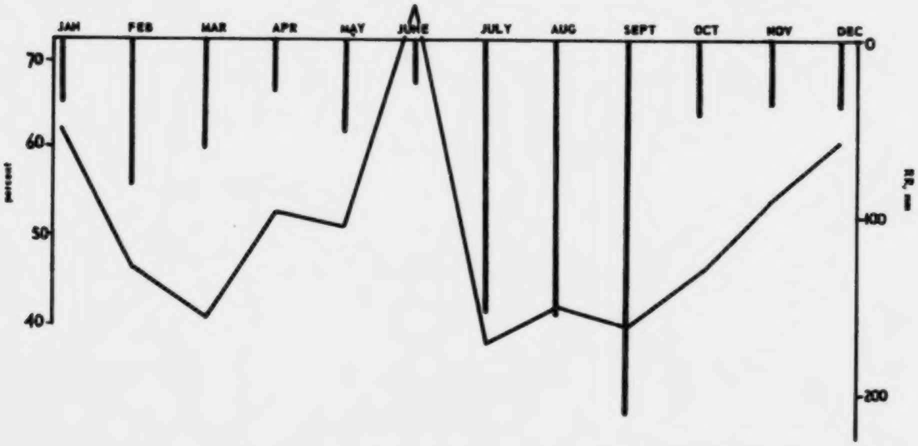

Figure 4. Relationship of harmonic pattern to precipitation data.

Cities influence the circulation, as do large industries that have a considerable heat output. It was observed that in Vlaardingen, a small town west of Rotterdam, the volatile products of the Shell refineries south of it could be smelled during situations with westerly winds. This could only be explained by assuming a vertical circulation due to the heating of the atmosphere over the refineries, air rising over them, and eventually descending over the town.

In order to detect this circulation, wind observations were made around the Shell complex during situations with westerly winds, and the divergence was determined.

Figure 5 shows the divergence pattern that has been computed from these observations, translated into vertical velocities in centimeters per second, based on the assumption that the divergence pattern is constant between the ground and 100 meters, the maximum height of the chimney stacks. The figure confirms that air rises over the region with largest heat output and descends to the north of the refineries. This result was based on a relatively small number of observations (17); however, direct measurements of the vertical motions with pilot balloons have given similar results.

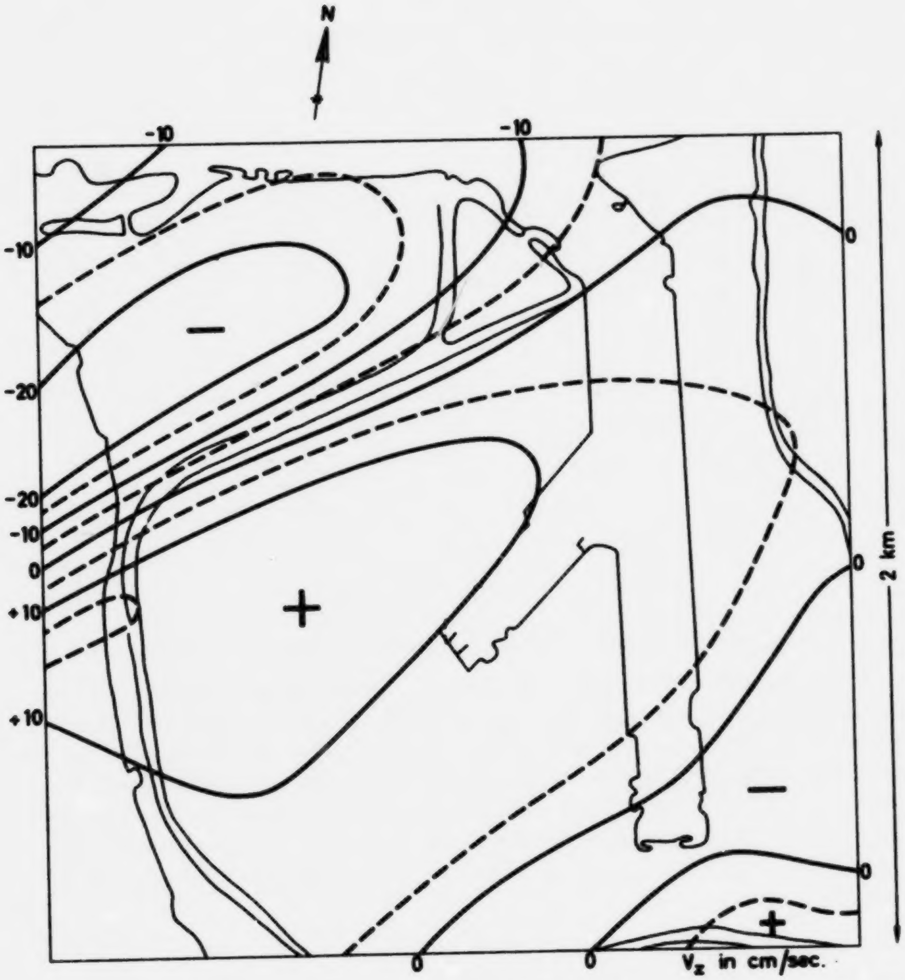

Figure 5. Computed wind divergence over industrial complex near Vlaardingen during westerly winds.

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DISCUSSION

FROM THE FLOOR: Plant damage around the steel mill, was it sulfur dioxide damage or chloride damage?

DR. SCHMIDT: Chloride.

MR. ROBINSON: In the diurnal stability pattern did you include a diurnal wind factor, also?

DR. SCHMIDT: No, it is very small. There may be an influence of land or sea breeze, even at Rotterdam, although it is 30 kilometers from the city.

We didn't have a measure for the daily variation of stability. We just looked at pollution and said, "Well, pollution shows a daily variation. And, can we understand that by ascribing it to the daily variation of stability." At the present time we do not have the means in the Netherlands to measure stability correctly. We have radiosonde observations, but it is hardly possible to say something about stability in the lower 100 or 200 meters with the observations as they are confined to two per day. What we did was just look at the daily variation of pollution, taking that daily variation as a measure of the daily variation of stability, then compare that daily variation of pollution with the amount of rain, for instance, the amount of rain giving an indication of the cloudiness, not a very exact indication, but giving an indication. And when we did that we found a connection between the two that we think we can understand.

Recent Developments in the Chemistry of Urban Atmospheres

JAMES P. LODGE, Jr., *National Center for Atmospheric Research*

Summary

The role of meterological factors in the transport of air pollutants is widely known. The effect of air pollutants upon weather and climate, however, has received far less attention. Probably the substance that has been studied most is carbon dioxide. It is generally agreed that the concentration of this compound in the earth's atmosphere has increased since the turn of the century, though the exact amount of increase is still unsettled. There is still less agreement on the resulting effect on the global heat balance. Urban air contains many more condensation nuclei than country air, and numerous unsupported statements have related this fact to smog formation. A better case can be made for an effect of sulfur dioxide, which is absorbed by fog droplets and is partially oxidized to sulfuric acid. This process should have a profound effect on fog persistence. Numerous other substances can be cited that must have some sort of modifying effect upon the urban microclimate.

What I would like to talk about has been in some measure preempted by Dr. Landsberg, but I am going to go over it again because perhaps stated from the viewpoint of a chemist it will be received with a little different emphasis. I want to talk about the atmospheric effects of chemical pollutants.

Considerable work has been done on the effect of the atmosphere on its load of chemical species. Some of this work has been of good quality, and some very poor, but nonetheless there has been substantial continuing research effort on the atmospheric transport of pollutants and on the changes undergone by pollutants as they are being carried. On the other hand, with one or two rather small exceptions astonishingly little active work has been done on the effect of chemical species, as such, on the weather, microclimate and climate of the urban area.

Certainly the best-known and most-studied effect is the so-called greenhouse effect of carbon dioxide; however, the exact magnitude of this effect still appears, so far as I can tell from current literature, to be under debate.

The amount of increase of carbon dioxide in the atmosphere over the past 60 years or so is not known. In 1961 we still do not have sufficiently accurate methods of measuring carbon dioxide to permit determination of this increase over a short period. The severity of the need for such methods was brought to my attention just a few days ago by a colleague who is trying to measure carbon

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dioxide at Point Barrow. He needs a method or device that will measure the very small gradients we would expect to find in the proximity of sinks, i. e., a device that might measure hundredths of a part per million carbon dioxide. I did not unduly encourage him, since this calls for an accuracy of roughly one in 30,000, which is very good accuracy for the best-established techniques of quantitative analysis of substances much easier to determine than carbon dioxide.

It has frequently been stated and was reiterated by Dr. Landsberg that cities are a source of very large numbers of condensation nuclei. The exact nature of their effect remains undemonstrated. Some very careful experiments concerning the nature of condensation nuclei formation in flames have been made; however, to my knowledge, only the rate of production of condensation nuclei by individual fuels has been demonstrated. Many of the condensation nuclei produced by human activity are so small they simply are not activated in the natural atmosphere.

Certain other individual species present in the particulate state in urban air have a substantial effect on fog persistence. For example, the output of sulfur dioxide reflected in an increase in the amount of sulfur trioxide or sulfuric acid has a substantial effect on fog persistence, as is now clearly demonstrated by work in London and elsewhere. Because of the extremely hygroscopic nature of sulfuric acid, there can be no question whatever that the presence of sulfur dioxide does result in an increase in the sulfuric acid content of the air, and thereby frequently stabilizes and perpetuates fogs at conditions well below water saturation.

There is still another effect of city gases such as sulfur dioxide, and this is the conversion of certain other species to sulfates and nitrates, and the like. For example, it has been shown by Jung that the one place large amounts of particulate nitrate are found in the air seems to be over coastal cities. In these cities salt fresh from the sea is brought into contact with oxides of nitrogen. Chemically this is very fascinating. The sulfates present in urban air seem to be ammonium sulfate and calcium sulfate. Sulfur dioxide is converted to sulfuric acid and thence to sulfate and seems in that state to tie up primarily with ammonia. Since lime and ammonia are the most active materials, they present the finest chance for reaction; nitrogen dioxide then comes along but must be contented to react with the only thing left, sodium chloride, which is less favorable for reaction. The sulfur dioxide has grabbed off everything else.

In a very clean atmosphere, if the sulfur dioxide were forced to react with the sodium chloride because of the absence of other good surfaces, we would have an interesting situation.

According to the data that I can find, the transition humidity for sodium chloride, i. e., the relative humidity at about room temperature at which it undergoes transition from a solid particle to a liquid drop, is about 74 percent. On the other hand, the corresponding transition humidity for sodium sulfate decahydrate, which is certainly the species that would be present under these conditions, is 93 percent. This would have a profound effect on fog persistence under these conditions.

I am not able to find the transition humidity for sodium nitrate in the literature; however, this would be very interesting since these chemical reactions do result in a shift in the relative humidity at which haze formation is initiated. This is an effect that to my knowledge has not really been investigated in relation to our present knowledge.

Another species put into the air of cities in quantity is soot. I find it very fascinating that soot is put out and we have talked about sootfall, and so forth, and yet nobody has tied this in with the series of experiments done by, among others, Dr. Florence Van Straten. These experiments indicate at least a good possibility of the initiation of convective activity by heat absorbed by clouds of soot.

Without passing for the moment on the validity of Dr. Van Straten's experiments, which I am not competent to assess and which I think no one else has fully assessed as yet, this certainly presents another source of possible meteorological change from pollutants.

Another interesting bit of recent knowledge is the fact that a number of species, most particularly metallurgical fumes, seem quite active as freezing nuclei at reasonably elevated temperatures; and still more recent knowledge, completely unassimilated as yet, that certain organic compounds are extremely active in promoting freezing of supercooled water.

Head in Australia demonstrated freezing on the surfaces of some fairly esoteric organic compounds at temperatures as warm as -2.5°. I will say, lest I frighten anyone, that this was under highly unrealistic conditions. Attempts to get classical-type cold-box nucleation by the same species have not been successful as yet. Head's work certainly indicates the possibility that cities can act as rather potent sources of freezing nuclei, and that this may, in fact, affect precipitation patterns over cities.

Another substance briefly mentioned by Dr. Landsberg, and certainly on a large scale neglected as a pollutant, is water vapor. Not too long ago, while I was still working here at Taft Center, I had a visitor who wanted to know how to remove his chief problem pollutant, which was water vapor. His stacks discharge quantities of water vapor just upwind of a major highway, and under these conditions you can have a severe pollution problem from water. There is, furthermore, the possibility already raised by Dr. Landsberg that this added water has an impact upon the total water balance of the city, in terms of increasing precipitation.

Finally, we have a rather more subtle effect of chemical species on the weather, a secondary effect. I can point out areas such as that region between the City of Houston, Texas, and the Gulf, for example, which have been thoroughly denuded of vegetation by uncontrolled discharge of pollutants - trees are dead, grass in many cases is gone. I think this is an effect that has been very little thought of, but we have denuded these acres of ground. We have reduced them to the bare earth. Certainly the effect of this on the heat balance must be great. No one would claim that the albedo of bare earth was identical with that of a grass- and tree-covered expanse.

In fact, as is well known, Dessens, working in Africa, has attempted to show, I think with relatively little success, actual cloud formation over a simply large black area of ground. If he puts in a little additional heat from a few burners, which we frequently do ourselves, by building a plant in the middle of such a desert, then he can get very fine formation of convective clouds. On one noteworthy occasion Dessens produced a tornado.

I am not trying to use scare tactics here. I am merely pointing out that we can hardly do anything without upsetting something in our balance of nature. We must weigh very carefully whether the results are worth the upset.

DISCUSSION

DR. MITCHELL: I was, of course, interested in the allusion you made to the fact that certain organic compounds might act as freezing nuclei at as high a temperature as -2.5°, and I just wanted to have you clarify, if you could, whether the evidence for this was in context of the small droplets as we find them in the atmosphere or at larger bulk water masses. This would be highly interesting.

DR. LODGE: Probably the first publication on this work was a brief note in Science, I think this past September 9, by R. B. Head of Melbourne. The chemical compound was melted on a microscope slide and allowed to solidify; very small drops were condensed on the solidified compound by chilling the microscope slide, and then observed for freezing.

Now the droplets themselves are small. The number of active sites is rather slight, and appears to coincide with some sort of unidentified lattice falls. The organic compounds in question are pure only to the extent of giving sharp melting points, and consequently I can't say beyond a shadow of a doubt that it is not due to some impurity. This I am planning myself to do a little work on. But there was one compound that did nucleate under these conditions at some times at temperatures as warm as -2.5°, and several above -10°. Primarily steroids, but also cholesterol, which is quite active in this as well as in some other things, and fluorene derivatives.

DR. HEWSON: I would like to ask Dr. Lodge what he estimates the improvements in the techniques for measuring carbon dioxide have been since the beginning of the century.

DR. LODGE: That's sort of a tricky question. I would say this: at best our methods now are very much better, a fine example being, on the days when they are working, - the nondispersive infrared instruments, such as those used by Keeling and Kanwisher, and others.

As I know you realize, there are many days on which these instruments are not working and our big difficulty is the total lack of a true referee method which permits calculation from first principles of what the concentration is that the instruments are measuring.

Their reproducibility can be made very good. Their absolute accuracy I think is largely unknown. It is my opinion that within a few years there should be methods that would be good to at least a tenth of a part per million. I think we are at last beginning to learn a few things about this, and I believe that the accuracy, precision, or discrimination, of the order of a part per million, necessary to sense gradients over water and so on, can be achieved by simply dodging the issue and measuring the gradient itself, directly, say, with a concentration cell, rather than undertaking to make two separate determinations and subtract.

DR. HILST: Dr. Lodge, what scale of length or area do you have in mind with regard to the changing of surface conditions and how this might affect the area. Is it an area of a square mile or are you thinking of counties, states, continents? Or all of it?

DR. LODGE: The specific case to which I alluded would be the area that we all know about, of the order of less than a square mile, an area which has been denuded simply by chemical action.

I am not referring specifically to paving. I am referring simply to the destruction of vegetation by uncontrolled discharge of pollutants.

DR. HILST: The effect of it, of course, would depend on how dynamically or hydrostatically stable or unstable the atmosphere reacted.

DR. LODGE: Absolutely.

FROM THE FLOOR: In view of the available methods for measuring pollution, data which are available from history, and what is liable to happen in the future, what is your view on the best indicator of trends of pollution, manmade pollution?

DR. LODGE: As things stand, and assuming that we don't learn a tremendous amount more about air cleaning than seems likely, I would stick by my statement of some years ago that carbon dioxide was probably the best index. Because it is produced in all human activity.

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A Climatological Evaluation of Precipitation Patterns Over An Urban Area

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Summary

A 13-year measurement program of urban rainfall distribution in a moderate-sized Illinois municipality is described. A dense raingage network with one gage per square mile has been in operation since 1948 in a community of 70,000 population. The monthly, seasonal, and annual precipitation patterns derived from the network data are discussed, and suggestions are offered concerning the possible urban influences on the patterns. The annual average precipitation pattern is compared with that from a nearby rural network to help evaluate the apparent urban-affected precipitation pattern obtained over the urban area. Recommendations are presented for the type of measurement program necessary to determine whether urban influences are producing measureable effects on the amount of precipitation over and downwind from the urban areas.

INTRODUCTION

Precipitation data from a dense network of raingages located in a moderate-sized urban area in central Illinois have produced a 10-year precipitation pattern which suggests the presence of urban influences. Statistical tests and theoretical considerations have been applied to these findings in hopes of determining whether the urban influences were responsible for additional precipitation on the downwind side of the urban area. From these investigations, conclusions as to other possible causes or explanations of the additional downwind precipitation are drawn, and suggestions are offered concerning urban precipitation measurement programs.

PREVIOUS FINDINGS

Before the Illinois study is discussed, it is appropriate to report briefly on some of the earlier findings. Undoubtedly, the most recent comprehensive resume of findings relating to urban effects on precipitation is the one by Dr. Landsberg.[1] Dr. Landsberg presented information on the various urban conditions affecting precipitation conditions as well as information on the observed precipitation increases in urban areas. He refers to other publications which show that urban areas, as opposed to rural areas, have been noted to have (1) more rainy days, (2) more thunderstorm days, and (3) more total precipitation. Various studies of European and North American conditions have shown that in urban areas precipitation can be expected to range from 5 to 10 percent above that in nearby rural areas. The number of days of light rain and of thunderstorms were reported to average from 11 to 18 percent more in urban areas than in nearby rural areas.

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*Read by Glenn E. Stout for Stanley A. Changnon, Jr.

Three factors are listed as principal causes of urban-induced increases in precipitation. These urban factors are additional condensation nuclei, additional water vapor, and turbulence resulting from thermal convection and increased surface roughness. Additional nuclei are designated as playing a more important role in the colder half-year when frontal precipitation in the central United States is most frequent. Because of this, Dr. Landsberg stated that the urban effect on precipitation is most pronounced in the colder half-year of humid continental climates.

DESCRIPTION OF ILLINOIS PROJECT

As so often occurs in science, a project started for one purpose eventually finds another and often an equally useful scientific objective. Such is the case with our urban precipitation project in Illinois.

In late 1948, the Illinois State Water Survey, in collaboration with the University of Illinois College of Engineering, installed nine recording raingages in Champaign-Urbana, Illinois. The locations of these gages, numbers 1 through 9, are shown in Figure 1. These were installed to furnish data for a hydrologic study of rainfall-runoff relationships on an urban watershed located in these adjoining communities.[2] At that time, two other recording raingages, numbers 11 and 12, were already in operation in the urban area, and by 1950 a twelfth gage, number 10 on the map (Figure 1), was installed. Data collection and routine analysis have been continuous since these 12 gages were installed. The data collected in the 1950-1959 period have been carefully re-analyzed and the results are used as a basis for the urban precipitation study. Extreme care was exercised in the installation of these gages in an effort to obtain comparable exposures, and since installation, the gages have had regular maintenance and servicing by one technician. Thus within normal performance limitations, the data from this network are considered to be of exceptional quality.

In many respects Champaign-Urbana, which is about 130 miles south of Chicago in east central Illinois, is in a uniquely suitable location for evaluating urban influences on precipitation.

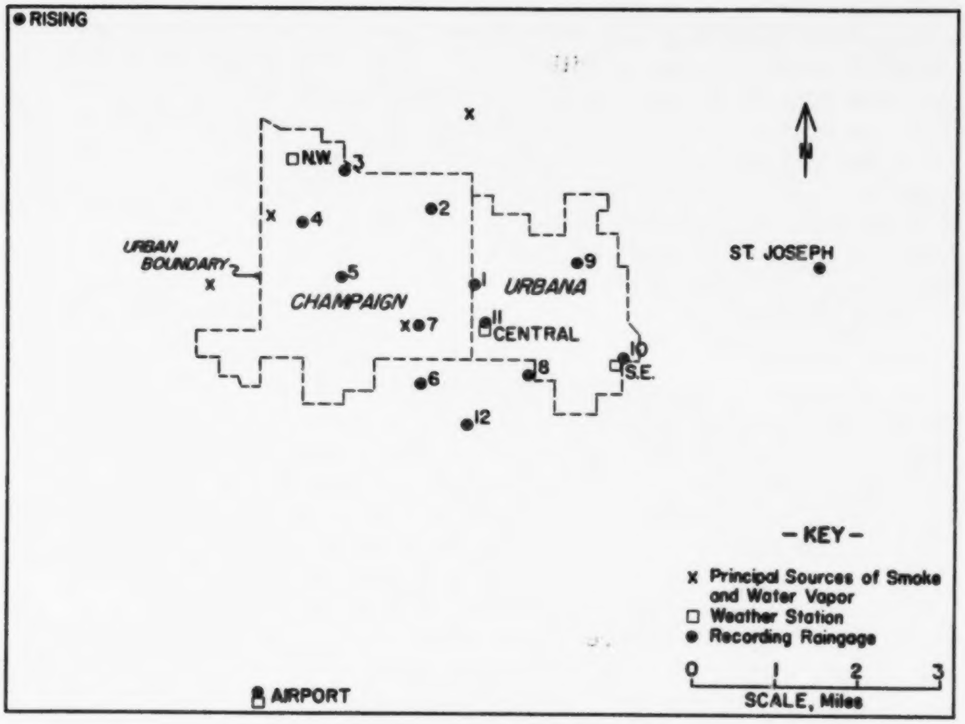
These adjoining cities, which are actually a single urban area, lie in an exceptionally flat featureless glacial plain with no significant changes in relief within 100 miles. The entire surrounding area also is devoid of any large-sized water bodies. The rural land is devoted to extensive cash-grain farming, chiefly corn and soybeans. The nearest urban communities with appreciable industrial development are more than 40 miles away. During the 1950-59 period, a complex of petro-chemical industries was built in a rural area 23 miles south of Champaign-Urbana. In general, it is believed that no natural or cultural factors that might significantly affect the distribution of precipitation exist in the region outside the urban area.

The twin cities function basically as a university-residential area. There are a few local industrial and heating plants as shown on Figure 1, but these are of minor importance and are not heavy industries. During the 1950-59 decade, the urban area has undergone growth. The corporate area was 9. 8 square miles in 1950 and was 11. 2 square miles by 1959; therefore, the raingage density has been about 1 gage per square mile. The urban population increased from 62, 000 in 1950 to nearly 77, 000 in 1959. As shown in Figure 1, the urban area is rectangular with the longer dimension of 5 miles lying east-west. The mean north-south width is 2. 5 miles. Impervious surfaces have been computed to be 38 percent of the total corporate area.[3] Until recent years, most of the urban area including the University of Illinois campus had an extensive tree growth but this has been greatly reduced by tree diseases. The only other local change of any possible significance was the addition in 1957 of a soybean processing plant in the vicinity of gage 4 (Figure 1).

In order to have a measure of precipitation for the surrounding rural area, records from three raingages, which were in operation during most of the 10-year period, were employed. These gages, as shown on Figure 1, are at Rising, a village 3 miles west-northwest of the urban area; at the University of Illinois Airport, 3. 5 miles south of the urban area; and at St. Joseph, about 7 miles east of the urban area. These are all unshielded recording raingages operated by the Illinois State Water Survey. Four weather stations in the area (Figure 1) were operated simultaneously during the July 1959 to June 1960 period to obtain detailed surface temperature measurements.

INTRODUCTION TO PROBLEM

The possibility of the existence of urban effects on the precipitation distribution in Champaign-Urbana is based on the premise that these effects will produce more precipitation in the


RISING
NW.
3
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URBAN BOUNDARY
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CHAMPAIGN
URBANA
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N
- KEY -
x Principal Sources of Smoke and Water Vapor
□ Weather Station
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SCALE, Miles
AIRPORT

Figure 1. Champaign – Urbana and Vicinity

eastern portions of the urban area than elsewhere in the urban area. This is considered valid since most precipitation systems and individual cells generally move from a westerly direction in this area.[4, 5] With such an average movement it is believed that urban effects on precipitation would not be realized until the precipitation system had passed over the western portion of the urban area. Fluctuations in the speed of cell movement, the stage of storm development, and the speed and direction of the surface winds would cause urban-affected precipitation conditions to maximize at different locations in the eastern half of the urban area, or possibly in the rural area east of Urbana.

Radar studies of precipitation cells and organized lines of precipitation in this area have shown that precipitation cells and lines generally move at speeds of 10 to 30 mph.[4, 5, 6] At an average speed of 20 mph and an average cell diameter of 5 miles,[6] a cell moving from the west over the urban area would require 30 minutes to pass entirely across the urban area. This is from the time the cell's leading edge reaches the western boundary until the trailing edge leaves the eastern edge of Urbana. Such a situation would require urban effects from Champaign (west) to act on the cell during the 15 to 20 minutes the cell is passing over Champaign. Since the average life cycle of a thunderstorm is on the order of 60 minutes,[6] this means that most thundershowers and rainshowers passing over Champaign-Urbana from the west spend nearly one-half their life cycle under the possible influence of the city. These statistics give some order of magnitude for the time-space relationship between precipitation conditions and this specific urban area.

If a 10-year maximization of precipitation occurred in the eastern urban area, this could be explained by any one of three possible factors: first, urban conditions may have produced additional precipitation (urban effects); second, more rain cells may have formed or maximized naturally over Urbana (natural variation of precipitation); and third, more sheltered exposures for the raingages may have existed in the eastern area (variability in gage exposures).

Description of the 1950-59 annual and seasonal precipitation patterns and the precipitation patterns displayed by individual precipitation periods in the 1958-1959 period will be presented, and from these and other supporting data, explanations will be offered relating to the three possible causes of the precipitation patterns observed.

AVERAGE ANNUAL PRECIPITATION

Figure 2 shows the average annual precipitation pattern

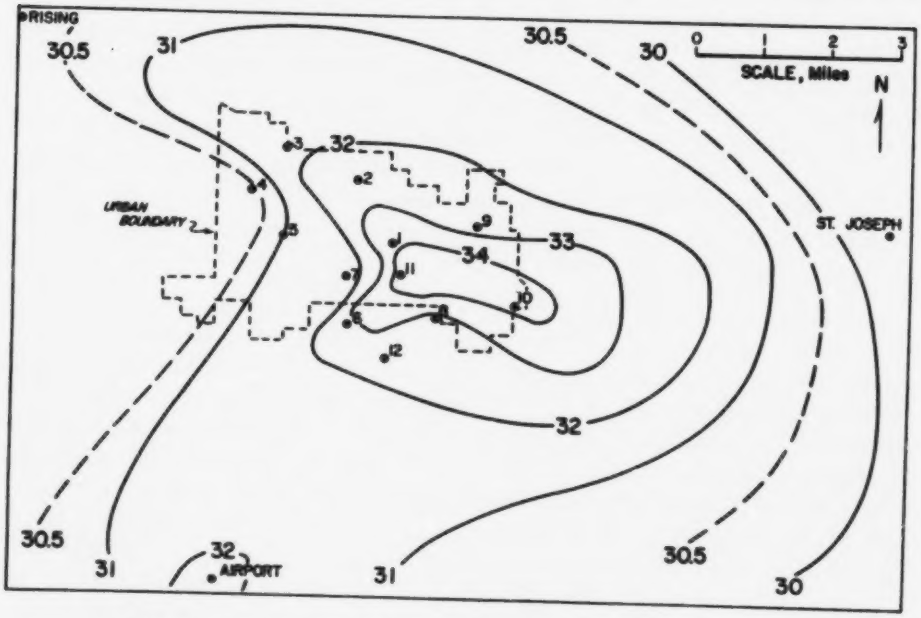

Figure 2. Average annual precipitation for 1950-1959, in inches.

based on the data for 1950-1959. Note that the highest values occurred over the ESE portions of the urban area. The entire urban area is the center of the region of greatest precipitation, which diminishes in all directions away from the urban area. In general, the rural to urban relationship is 30 to 34 inches, respectively, and the difference amounts to 12 percent. This compares favorably with annual percentage differences of 5 to 10 percent reported by Dr. Landsberg.[1]

Although not discernible in Figure 2, the average annual precipitation pattern for 1950-1959 across Missouri, Illinois, and Indiana had a west-to-east increase, as based on First-Order Station data. In the area of Champaign-Urbana this west-to-east increase was at the average rate of one inch per 20 miles; this indicates that with no urban influence a west-to-east increase of 0.25 inch should have occurred from the west side of the urban area to the east side.

A 10-year precipitation record in a humid continental climate can be considered of questionable significance, since it may represent an abnormal period because of temporal and spatial precipitation variations. One estimate of the possible validity of the maximum in the east urban area was obtained by comparing long-term records of two urban raingages. Gage 11 in the high area (Figure 2) has been in operation since 1903, and gage 12, with a 10-year average nearly 2 inches lower than gage 11, has been in operation since 1930. The 1930-1959 average annual precipitation at gage 11 is 37.3 inches compared to 34.5 inches at gage 12. The 30-year average annual difference of 2.8 inches is in the same order of magnitude as that shown in Figure 2, and thus lends credulence to the 10-year pattern. The 45-year normal annual value for gage 11 is 36.6 inches; therefore, the 34.4 inches recorded as an average for the 1950-1959 period represents a below-normal departure, which is largely a result of drought conditions in 1952-1955.[7]

The validity of the pattern shown in Figure 2 also was investigated by inspecting the frequency distribution of the annual ranks based on the annual totals of each of the 12 urban gages. The 12 values in each year were ranked from high (first) to low (twelfth), and the rank frequencies for the 10 years were then inspected. This was used to determine whether the areas of high and low average precipitation were a result of extremes in just a few of the 10 years. The rank frequencies for the 12 gages and an average rank determined for each gage are given in Table 1. The 6 gages located in the east half of the urban area had 25 of the first, second, or third ranks, and this total is 10 more than would be expected if the ranks were normally distributed among all 12 gages. There was a distinct absence of low ranks (tenth,

TABLE 1

NUMBER OF TIMES EACH GAGE ACHIEVED VARIOUS RANKS BASED ON ANNUAL TOTALS AT EACH URBAN GAGE 1950-1959 PERIOD

	Distribution of rank by gage number											
Ranks	2	3	4	5	6	7	8[a]	9[a]	10[a]	11[a]	12[a]	1[a]
1-2-3	1	1	1	1	1	0	2	2	6	8	5	2
4-5-6	4	2	2	2	4	0	1	5	3	2	2	3
7-8-9	3	6	0	3	3	5	4	3	0	0	1	2
10-11-12	2	1	7	4	2	5	3	0	1	0	2	3
Average Rank	6	9	11	10	5	12	8	3	2	1	4	7

[a] Indicates gages located in the east half of the urban area.

eleventh, or twelfth) among the six easternmost gages. Only nine of these low ranks were recorded, whereas 15 would normally be distributed in the east. Also four of the six easternmost gages had the highest average ranks. These data support the climatological validity of the annual pattern shown in Figure 2 and indicate that this annual maximization in the east was a repetitive process in

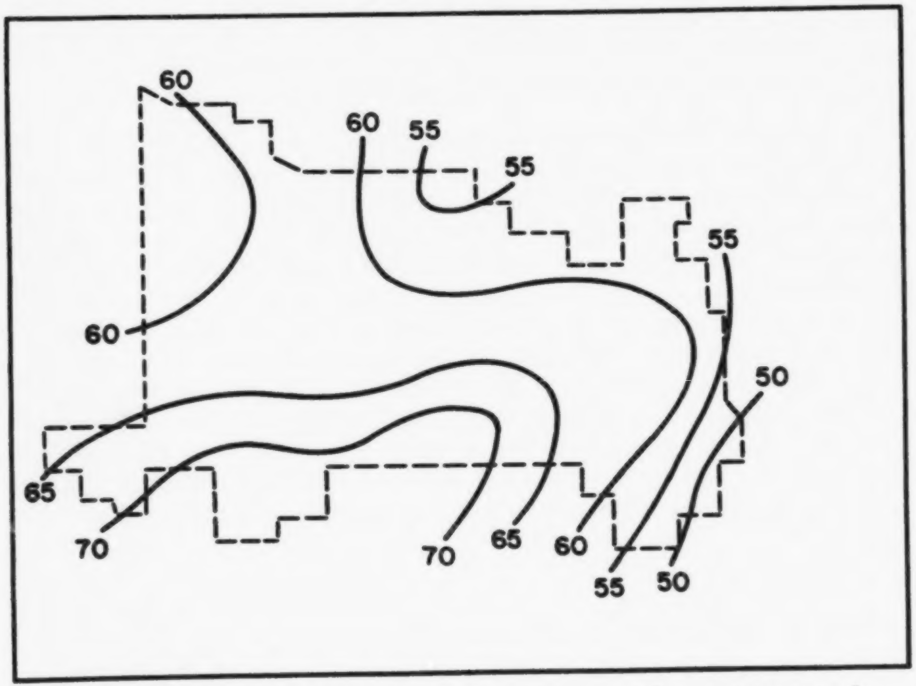

Figure 3. Total number of 30-minute to 24-hour amounts ≥ 2-year recurrence value, 1950-1959

most years. Either gage 10 or 11 ranked first or second in 7 of the 10 years. In two of the remaining three years, gages 8 and 9 achieved rank one. In only one year, 1959, did the maximum precipitation and highest ranks occur on the west side of the cities.

The possibility that the 10-year annual pattern might be a derivative of the frequent occurrence of excessive rainstorms in Urbana was also investigated. In Figure 3 the urban distribution of storms in 1950-1959 with recurrence intervals equal to or greater than 2 years and with durations ranging from 30 minutes to 24 hours is shown.[8] The greatest frequency of such storms was in the southwestern urban area and the lowest in the eastern area, indicating that the average annual precipitation maximum in the east urban area was not derived from repeated occurrences of excessive rainstorms in that area.

Several studies in Europe have shown that an urban area, through urban influences, experiences more thunderstorms than nearby rural areas.[1] An examination of the records from the Airport weather station and the Central weather station (Figure 1) revealed that during a 5-year period of comparable records for the hours between 0700 and 1800 CST the urban station recorded on the average three more thunderstorm days per year than the Airport station. The urban average annual 5-year value was 45 thunderstorm days, which is 2 days less than the normal, based on 54 years of record.[9] This finding tends to corroborate the belief that urban effects produced by Champaign-Urbana influence precipitation systems passing and developing over the cities.

Other investigators have analyzed data on the frequency of days with precipitation and concluded that an urban effect exists. A European study revealed Munich had 11 percent more days with precipitation in the range of 0.004-0.2 inch than the surrounding country.[1] An urban increase of 12 to 18 percent in these light rains was found in the Ruhr region of Germany.[1] In Illinois a comparison of 8 years of records showed that the mean annual number of days with light precipitation (0.004-0.24 inch) was 69 at the Airport gage (Figure 1), compared with 78 at urban gage 11. This is an increase of 13 percent, which compares favorably with the percentages noted in Europe. For days with precipitation of 0.25 inch or more, there was no significant difference between the average for the Airport (41 days) and that for gage 11 (42 days).

AVERAGE SEASONAL PRECIPITATION

In Figure 4 the four seasonal average isohyetal patterns are portrayed. Maximization of precipitation over the eastern half of the urban area is evident in all four seasons. In Table 2 the values considered the best approximations of the rural or unmodified urban precipitation and those best representing the modified urban precipitation are shown. These data reveal that the greatest percentage excess in the urban area occurs during the colder seasons; this agrees with Landsberg's findings for Tulsa.[1] The least excess occurs during the summer.

The 30-year average seasonal values for gages 11 and 12

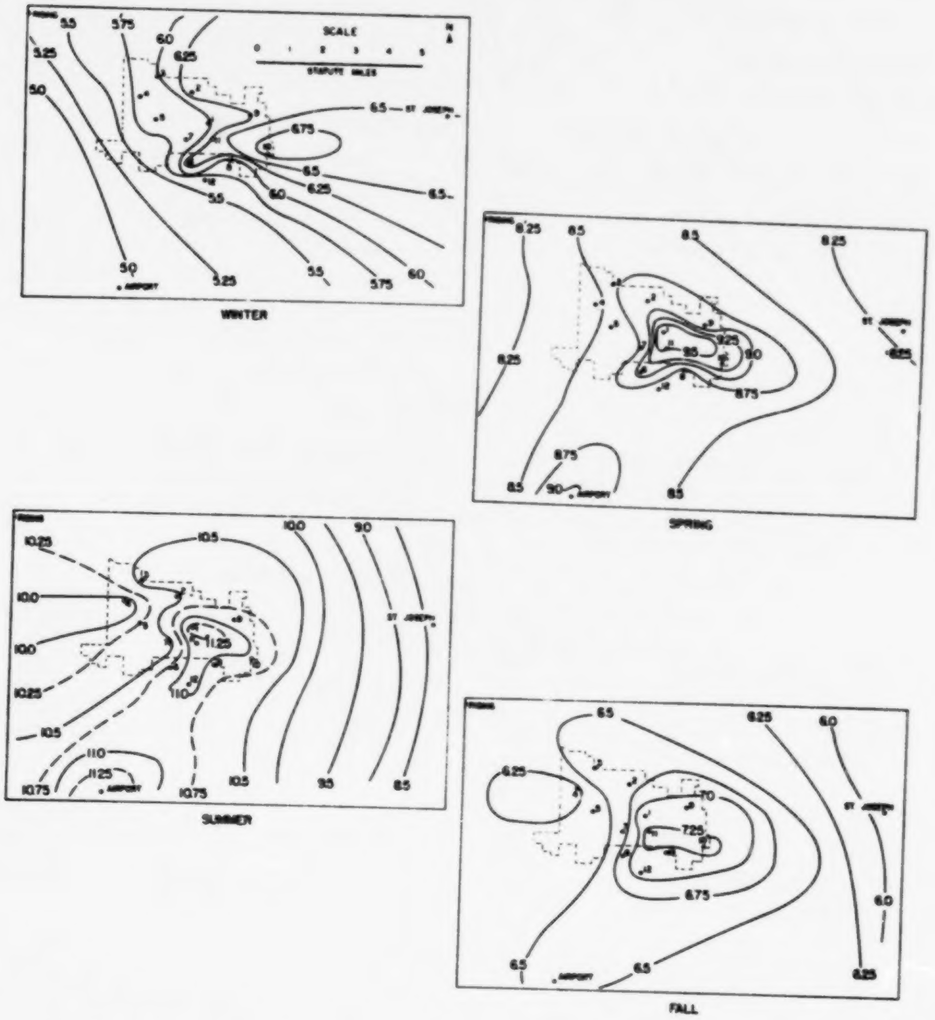
SCALE
STATUTE MILES
ST JOSEPH
AIRPORT
WINTER
SPRING
SUMMER
FALL

Figure 4. Average seasonal precipitation patterns for 1950-1959 in Champaign-Urbana and Vicinity.

TABLE 2

COMPARISON OF AVERAGE SEASONAL PRECIPITATION FROM RURAL AND UNMODIFIED URBAN AREAS WITH THAT FROM MODIFIED URBAN AREA 1950-1959

	Season			
	Winter	Spring	Summer	Fall
Rural and unmodified, urban precipitation, in.	5.25	8.25	10.25	6.25
Modified urban precipitation, in.	6.25	9.50	11.00	7.25
Difference between rural and urban-modified, in.	1.00	1.25	0.75	1.00
Percentage excess in modified urban area	16	13	7	14

TABLE 3

COMPARISON OF AVERAGE SEASONAL PRECIPITATION AMOUNTS AT GAGES 11 AND 12 BASED ON 30-YEAR AND 10-YEAR PERIODS OF RECORD

	Seasonal precipitation, in.			
	Winter	Spring	Summer	Fall
1930-1959 Period				
Gage 11 average	6.55	11.05	11.05	8.67
Gage 12 average	5.43	10.11	10.65	8.17
Difference, 11-12	1.12	0.94	0.40	0.50
1950-1959 Period				
Gage 11 average	6.47	9.50	11.08	7.31
Gage 12 average	5.63	8.64	11.16	7.21
Difference, 11-12	0.84	0.86	-0.08	0.10

are shown in Table 3. Gage 12 represents a more rural location than gage 11 in the urban modified area. The differences between these two gages, based on data for the 1950-1959 period, are shown also in Table 3. In general, the average seasonal values for both gages, based on the more reliable long-term record, compare favorably with those based on data for 1950-1959. Only the 1950-1959 spring and fall averages are lower than the 30-year values. A comparison of the differences between the values from the two gages reveals that seasonal differences based on the two periods of record are remarkably similar. These findings tend to substantiate the fact that although the 1950-1959 precipitation was somewhat below normal at a point, the variations shown between points may be representative of those expected over a longer and, climatologically, a more reliable period of time.

Winter - The winter precipitation pattern (Figure 4) reveals a condition not found in the other three seasons. The east side urban area high extends to the east into the rural area, indicating that if urban influences do produce additional winter precipitation the resultant greater precipitation is prolongated in time and continues over a greater distance than in the other seasons. This could be explained partially by the greater winter frequency of more extensive frontal precipitation systems, and by the fact that, in general, urban nuclei effects on precipitation systems are most pronounced in the winter season.[1] The percentage excess listed in Table 2 is highest for winter also.

Spring - The area of maximum precipitation in spring apparently extends 2 or 3 miles east of Urbana, but at the St. Joseph rural location the average value is much lower than the urban maximum values. A secondary high in the isohyetal pattern appears at the Airport gage. The increase in precipitation across the urban area is much more rapid over a short distance, from 8. 75 to 9. 5 inches in 1 mile, than any comparable increase over a short distance in winter, although this could be largely a sampling variation.

Summer - Summer is the only season in which the eastside urban high apparently does not extend into the rural area to the east. The presence of a rural average, at the Airport, greater than the values in the urban high (Figure 4) strongly suggests that the summer pattern may largely be a result of natural rainfall variations. At least, natural variability, which maximizes in the summer, helps to confuse the assignment of any increases to urban influences. The differences between the averages of the three rural gages also substantiate this conclusion. The Airport value is 11. 49 inches, the Rising value is 10. 41 inches, and the St. Joseph value is 8. 33 inches. The maximum difference between these three values exceeds any variation observed between any of the 12 urban gages. Landsberg has stated that urban influences on precipitation have least effect in the summer, or warm season,[1] and this is supported in Table 2,which reveals that the lowest seasonal percentages of urban excess occurred in the summer.

Fall - The fall isohyetal pattern closely resembles the spring pattern; however, changes in precipitation across the urban area are more gradual in fall than in the spring. The urban excess in fall produces the second greatest seasonal percentage, as shown in Table 2.

EVALUATION OF INDIVIDUAL PRECIPITATION PERIODS IN 1958-1959

All precipitation periods in 1958 and 1959 on the urban area network were analyzed to investigate more closely the conditions with which precipitation increases occurred in the eastern portion of the urban area. As stated previously, precipitation maximization in the east was considered indicative of possible urban influence. A precipitation period was defined as a distinct period of precipitation, with no precipitation 6 hours before the period began and none for 6 hours after the period ended. This delineation of the data yielded 262 precipitation periods in the 2 years. Each of these precipitation periods was mapped and isohyetal patterns were drawn.

The urban area was divided by two lines, as shown in Figure 5, so that a western, eastern, northern, or southern half

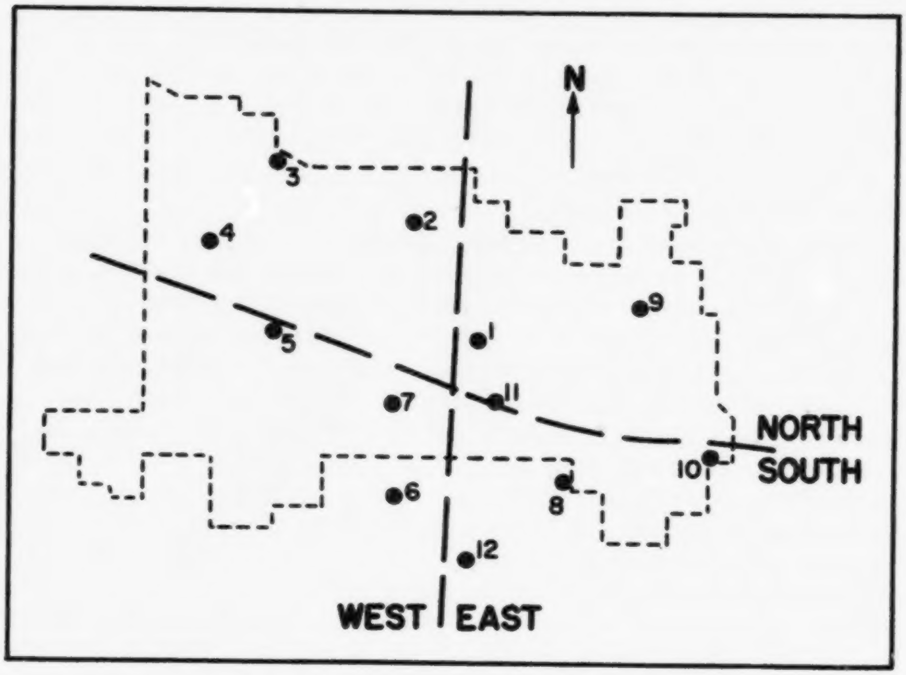

Figure 5. Division of urban area for study of precipitation patterns

of the urban area could be delineated. Each directional half had six raingages. Based on this form of separation, each isohyetal pattern for a precipitation period was classified according to the half containing the maximum precipitation. This half was defined as the area containing the four highest precipitation values; if no half had the highest four values, or if the 12 values showed very little percentage difference, the pattern was considered "flat" or without a definite maximum. Consequently, there were five potential pattern classifications.

A pattern with a maximum in the eastern half was considered to be a pattern representative of urban influences on precipitation. The other four patterns were considered to represent natural variations in precipitation. Therefore, the frequency of periods with east-half maxima was examined statistically in relation to the frequency of other patterns. The temporal distribution of precipitation occurrence, the surface winds, and the types of synoptic situations which occurred with these 262 rain periods also were studied, compared, and evaluated.

Frequency Distribution. The annual and seasonal frequencies of the periods associated with the five different patterns are shown in Table 4. If all patterns were normally distributed, each of the percentage values in Table 4 would be 20; however, examination of the percentages for the cases with east-half maximum values indicated that in each season and for the year this pattern easily exceeded the normal expected frequency of occurrence. In the winter and fall seasons the percentages are almost twice those expected, and the spring and annual percentages are more than 50 percent greater than expected. Only in summer is the percentage near the normal expected value. Without elaborate statistical testing, which is not in order with this sample size, it appears that the high percentage of cases with east-area maxima in the fall and winter achieve particular significance because no other comparable high percentages occurred in these two seasons. The high east area percentage in spring is exceeded by the flat pattern percentages, and this factor tends to lessen the significance of the high spring value in the east.

From these data it could be concluded that urban influences affect one precipitation period in 10, causing a maximization in the eastern half of the urban area. Normally, 2 out of 10 precipitation periods are expected to maximize there, but on an annual basis the 1958-1959 data indicate that 3 of 10 periods maximized in that urban locality. In all four seasons more precipitation periods with an east-half maximum occurred than expected. In both the fall and winter season, nearly 4 out of every 10 precipitation periods maximized in the eastern half of the urban area.

TABLE 4

ANNUAL AND SEASONAL FREQUENCIES OF PRECIPITATION PERIODS WITH DIFFERENT TYPES OF ISOHYETAL PATTERNS

	Area of Maximum Precipitation Values					
	East	West	North	South	None (flat)	Total periods
Winter						
Number of periods	18	5	1	8	14	46
Percent of total	39	11	2	17	31	--
Spring						
Number of periods	28	14	5	6	29	82
Percent of total	34	17	6	7	36	--
Summer						
Number of periods	18	18	9	15	15	75
Percent of total	24	24	12	20	20	--
Fall						
Number of periods	22	12	4	7	14	59
Percent of total	37	20	7	12	24	--
Annual						
Number of periods	86	49	19	36	72	262
Percent of total	33	19	7	14	27	--

Hourly Occurrence of Precipitation. The time of occurrence of precipitation with these various precipitation patterns also was investigated. A count of the number of times each hour had precipitation was made for (1) the precipitation periods with maxima in the east half and (2) all the remaining precipitation periods. The results of this analysis are shown in Table 5. If it is assumed the data derived from the other four patterns represent a near normal hourly distribution of precipitation, any significant deviations from these distributions exhibited by data from periods maximizing in the east would be of interest.

In the winter the east-half maximization periods produced precipitation most frequently in the hours from 1400 to 2200 CST, whereas for all the other periods precipitation was most frequent from 0400 to 1200. In the spring the periods maximizing in the east area were most frequent from 1200 to 2000 CST, whereas the other patterns maximized from 1800 to 0200 CST. In the summer, the precipitation periods with east-half maximization were most frequent at hours nearly the same as those with the other periods of precipitation, although the other patterns indicated a secondary maximization of hourly frequencies from 1800 to 2000 CST. In the fall the east-half maximum periods produced precipitation most frequently between 1000 and 1400 CST, compared with 0600 to 1000 CST for the other patterns. This tendency for a greater frequency later in the day with the east-half maximization periods also was characteristic in winter. On an annual basis, the precipitation periods in which a maximization occurred on the east half of the urban area produced precipitation more frequently during the afternoon and early evening hours, whereas the other types of patterns produced precipitation more uniformly distributed in time. The possible causes for these peculiar time distributions associated with precipitation periods

TABLE 5

DISTRIBUTION OF HOURS WITH PRECIPITATION ASSOCIATED WITH PRECIPITATION PERIODS MAXIMIZING IN THE EAST AND WITH ALL OTHER PRECIPITATION PERIODS

	Percent of total hours									
	Winter		Spring		Summer		Fall		Annual	
2-hr period (CST)	East max.	Other patterns	East max.	Other patterns	East max.	Other patterns	East max.	Other patterns	East max.	Other patterns
2400-0200	4	6	3	10	5	4	6	8	5	7
0200-0400	5	8	4	7	7	6	5	7	5	77
0400-0600	5	9	5	7	5	6	7	7	5	8
0600-0800	7	11	6	8	10	7	8	11	7	9
0800-1000	8	11	8	6	11	8	9	12	9	9
1000-1200	9	9	11	7	13	9	10	8	10	8
1200-1400	10	9	12	6	10	14	10	8	11	9
1400-1600	11	8	14	8	11	12	9	8	11	9
1600-1800	10	8	13	9	8	8	9	8	10	8
1800-2000	12	7	12	10	7	12	10	7	11	9
2000-2200	12	7	8	10	6	8	9	8	9	8
2200-2400	7	7	4	12	6	6	8	8	7	9

maximizing in the east will be discussed later.

The average precipitation periods with an east-half maximization were 12. 1 hours in winter, 6. 5 hours in spring, 3. 4 hours in summer, and 10. 1 hours in fall. The durations for fall and spring were slightly greater than those based on all the other patterns.

Surface Wind Conditions. It is assumed that two of the urban influences on precipitation are additional condensation nuclei and water vapor. For these factors to influence the moderately small Champaign-Urbana area most actively, they would have to be brought into the precipitation systems west of the urban area, since most precipitation systems move from the west. This would give these two factors more time to act on the precipitation systems. To produce an east-area maximization, the low-level winds prior to the start of precipitation should be moving across the urban area in a direction which would allow these influences to be swept downwind into the clouds to be affected.[10] Because of the relatively small size of the urban area under consideration, however, a northeast, east, or southeast low-level wind direction would appear to be most favorable to obtain an upwind movement of atmospheric nuclei and water vapor for earlier entrainment into the precipitation-producing system entering the urban area from the west. Winds at and prior to precipitation are considered in this evaluation rather than wind conditions during precipitation, because precipitation tends to remove nuclei from the air thereby lessening this urban influence.[11] Previous radar studies have shown that most precipitation cells in this area move from the west-southwest, west, and west-northwest.[5] To support this supposition on air movement, the precipitation periods with maximization in the east should be preceded by a greater frequency of winds from the northeast, east, and southeast than are all the other four types of precipitation patterns. Data presented in Table 6 do not substantiate this assumption, although surface winds are not always

TABLE 6

FREQUENCY OF SURFACE WIND DIRECTIONS PRIOR TO AND AT THE BEGINNING OF PRECIPITATION PERIODS

Precipitation pattern	Total periods	Direction frequency, %							
		N	NE	E	SE	S	SW	W	NW
Maximum in east	86	4	11	9	5	12	37	15	7
All other patterns	176	14	8	17	12	16	19	9	5

indicative of the low-level wind field. 25 percent of the east-half maximum periods had surface winds moving from the three easterly azimuths across the city, whereas of all other periods 37 percent had surface winds from these three directions.

These findings derived from the surface wind data could be interpreted as refuting the theory that urban effects helped to produce more frequent maximization of precipitation in the east, because favorable surface wind directions were not frequent. At least, the surface wind conditions with east-side precipitation maxima do not substantiate the theoretical considerations.

Synoptic Conditions with Precipitation Periods. The frequency of various synoptic situations associated with the 262 periods is shown in Table 7. Cold and warm front classifications include pre-frontal activity related to their presence. Relating the cause of precipitation to various synoptic types is fraught with problems of interpretation, but it is believed that the frequencies shown in Table 7 are in the right order of magnitude and that it is safe to use such data to draw limited conclusions. As expected, cold fronts were the most frequent synoptic condition that produced precipitation, and stationary fronts were the second most frequent type. Surface lows, air mass instability, occluded fronts, and warm fronts had almost equal frequencies.

TABLE 7

ANNUAL AND SEASONAL FREQUENCIES
OF SYNOPTIC TYPES ASSOCIATED WITH
THE PRECIPITATION PERIODS IN 1958-1959

Season	Warm Front	Cold Front	Stationary Front	Occluded Front	Surface Low or Trough	Upper Trough	Air Mass	Total Periods
Winter	2	11	5	10	8	4	6	46
Spring	11	20	15	10	13	2	11	82
Summer	3	29	23	0	9	3	8	75
Fall	7	21	11	4	8	5	3	59
Annual	23	81	54	24	38	14	28	262

In Table 8 the numbers of different synoptic types associated with the five different precipitation patterns are expressed as percentages of the pattern total. Only with the air mass and stationary front types is there a semblance of comparable percentages among the five patterns. If the difference between the number of west and east maximizations (Table 4) is assumed to represent

TABLE 8

SYNOPTIC TYPES ASSOCIATED WITH FIVE URBAN PRECIPITATION PATTERNS

	Percent of each pattern total				
Synoptic type	East maximum	West maximum	South maximum	North maximum	flat
Warm front	7	10	0	16	13
Cold front	35	33	36	48	17
Stationary front	20	30	22	21	14
Occluded front	12	0	0	0	19
Surface low-trough	13	15	11	5	21
Upper trough	1	2	17	5	6
Air mass	12	10	14	5	10

urban influences, then the significant differences between east and west synoptic percentages shown in Table 8 could indicate the synoptic condition most favorable for maximizations in the east. The only difference favoring the east is associated with occluded fronts. Comparison of all the percentages in Table 8 reveals that the flat pattern percentage for occluded fronts exceeded that same percentage with east maximizations; however, it could be concluded that the only significant synoptic condition relating to maximization in the eastern urban area is the occluded frontal type.

For a closer inspection of the synoptic conditions associated with eastern urban area maximizations, the seasonal frequencies are portrayed in Table 9, and these frequencies are also expressed as percentages of the seasonal totals in Table 7. It has been stated previously in this section that apparently: (1) the seasons during which the east-half storms occurred most frequently were winter, fall, and spring; and (2) the synoptic type exhibiting the most significant difference in percentages, associated with east-half patterns, was the occluded front. These statements are augmented by the data in Table 9. In winter and spring 40 percent of the occluded front periods maximized in the east, and in the fall, 50 percent.

Summary. The theory that urban effects increase precipitation appears to be substantiated by many of the results derived from the investigation of 262 precipitation periods. Almost twice as many periods as expected had a maximum of precipitation in the eastern half of the area. Furthermore, the seasons when these events occurred most frequently were winter and fall, closely followed by spring. Therefore, the cases that supported

TABLE 9

SEASONAL NUMBER AND PERCENT OF SYNOPTIC TYPES ASSOCIATED WITH PRECIPITATION MAXIMUMS IN THE EASTERN HALF OF THE URBAN AREA

Season	Warm front	Cold front	Stationary front	Occluded front	Surface low-trough	Upper trough	Air mass
Winter							
Number	1	5	3	4	4	0	1
Percent of total seasonal cases	50	46	60	40	50	0	16
Spring							
Number	3	8	3	4	3	1	6
Percent of total seasonal cases	27	40	25	40	23	50	56
Summer							
Number	0	8	7	0	1	0	2
Percent of total seasonal cases	0	27	30	0	11	0	25
Fall							
Number	2	9	4	2	4	0	1
Percent of total seasonal cases	29	43	36	50	50	0	33

the hypothesis of urban-induced precipitation occurred largely in the colder half-year, and this agrees with previous findings.[1]

The marked tendency for precipitation with an east-half maximization to occur later in the day than the other precipitation patterns during the winter and fall, and more frequently during the period from midday to late afternoon than the other precipitation patterns suggests the possibility that a diurnal heating influence might be acting to produce maximization of precipitation in the east. Surface winds prior to the beginning of precipitation periods maximizing in the eastern area were not frequently from easterly azimuths, however, a condition believed favorable for bringing the urban nuclei and water vapor influences into the cloud and precipitation systems. The only synoptic type associated with precipitation periods maximizing in the east more frequently than elsewhere was the occluded front.

EVALUATION OF CAUSES FOR URBAN PRECIPITATION MAXIMIZATION.

Considerable data have been presented concerning the daily, seasonal, and annual distribution of precipitation during all or parts of the 1950-1959 decade. It has been repeatedly suggested that urban influences could be largely responsible for the maximization of precipitation in east side urban areas. Champaign-Urbana urban-rural differences in total precipitation, days of rain, and days with thunderstorms were statistically similar to results found elsewhere, and attributed to urban influences on atmospheric conditions. Based on this comparison it could be superficially concluded that the findings of the 10 years of precipitation data collected in Champaign-Urbana were a result of urban meteorological influences. Knowledge of the spatial precipitation variability encountered in this climate through natural influences and from varying raingage exposures, plus the lack of definite measured proof of the action of urban influences, however, leaves the discerning observer unsure of the causes for the observed variations in precipitation. Therefore, a discussion of each of three possible causes for the variation follows.

Raingage Exposures. Evaluating precipitation catch has long been a problem in meteorology and climatology[12] because of differing raingage exposures. Also the effects of various methods of shielding raingages have been measured in many different experiments with varying results. Weiss and Wilson[13] reported that amounts of precipitation measured when various shielding techniques are used vary from 87 percent to as high as 340 percent of unshielded catches. From the values of the 17 experiments they listed, the median value selected indicated that shielded raingages catch 9 percent more precipitation than unshielded gages. This percentage difference is comparable with the annual difference of 12 percent found for the 10-year period in Champaign-Urbana. That is, if the gages in the eastern urban area generally were more shielded than those in the west, a west-to-east increase comparable to that experienced in 1950-1959 might result. To derive such a conclusion it must be assumed that exposure differences caused by obstacles in an urban area might be comparable with those differences between shielded and unshielded gages. None of the 12 gages were shielded. All the raingages were assumed to have similar gage wind eddies, but it is possible that site and environment wind eddies, because of differences in gage exposures, varied sufficiently in magnitude to create wind eddy differences which approximated the differences in gage eddies obtained between shielded and unshielded raingages.

In further support of the possibility that gage exposures are responsible for the Champaign-Urbana differences, it should be noted that shielding effects are much more pronounced for snowfall than for rainfall.[13] Since the average urban snowfall in the 10-year period was 11.8 inches, or about 1.2 inches of water, extreme exposure differences between the rural gages and the central urban gages might produce a water measurement difference of about 0.5 inch. This difference is based on a median percentage determined from 18 field experiments reported by Weiss and Wilson; these experiments showed that the snow catch of a shielded gage is 160 percent of the snow catch of an unshielded gage. As noted in Table 2, the average urban-rural precipitation difference in winter was 1.0 inch; shielding variations therefore could account for 50 percent of the observed difference.

Since exposure variability can be shown to be a possible cause for observed precipitation difference, a method was developed to obtain a quantitative measure of the exposures of the 12 urban gages for comparison purposes. No wind instruments were available to perform this.

The method initially consisted of measuring with a transit the amount of horizon blocking afforded by surrounding obstacles which extended above the horizon line of the raingage tops. Since the amount of wind passing a gage orifice is inversely related to the gage catch, the amount of blocking or shielding by surrounding objects should be directly related to the catch. The exposure in blocking was computed as the number of degrees of vertical blocking in each of the eight 45-degree sectors in azimuth, with each sector centered on the eight basic compass directions. Since no object at any gage had a vertical angle greater than 30 degrees, the total possible blocking in any sector was 45 degrees times 30 degrees, or 1350 degrees, and the amount of blocking in each sector at each gage was expressed as a percent of this total.

Secondly, these sector blocking percentages were normalized to wind directions by multiplying each by the corresponding annual wind direction frequency during the occurrence of precipitation. Therefore, excessive gage blocking to the north from where precipitation winds are infrequent would not achieve as much statistical significance as equal sector blocking to the south from where precipitation winds are frequent. Unfortunately this calculation does not include wind speed, but it does provide a relative measure of the effect of site and environment shielding around the gages.

The results of this method for evaluating exposures of the 12 gages are shown in Table 10. A comparison of these results with those in Table 1 indicates that, in general, there is very little agreement for any gage between the rank of the precipitation catch and the shielding rank. A high shielding factor should relate directly with a greater precipitation catch. If the rank values based on precipitation amounts in Table 1 are added, the easternmost six urban gages have a score of 25, compared with a score of 53 for the westernmost six gages. A similar summation of ranks based on the shielding factors in Table 10 provides a total score of 41 for the easternmost gages and 37 for the westernmost gages. This indicates no material difference between the overall exposures of the gages in the western and eastern halves of the urban area.

TABLE 10

ENVIRONMENTAL SHIELDING FACTORS FOR 12 URBAN RAINGAGES

Gage	Shielding factor by wind direction								Total shielding value	Rank based on shielding total
	N	NE	E	SE	S	SW	W	NW		
1	8.4	2.6	3.2	2.9	13.8	4.4	1.5	4.0	40.8	1
2	3.0	1.1	0.3	0.2	2.9	0.7	1.0	2.8	12.0	7
3	1.7	4.6	3.7	1.5	7.8	0.8	2.4	1.1	23.6	2
4	1.3	1.8	1.1	0.9	2.8	1.3	0	0	9.2	9
5	1.3	1.3	1.3	0.9	2.5	2.1	3.5	1.3	14.2	5
6	0	0.7	1.8	3.2	9.1	0.2	0.2	0	15.2	4
7	1.0	1.3	1.3	0.3	0.6	0.4	1.9	1.5	8.3	10
8	1.3	0.2	0	0	0	3.0	0.6	1.2	6.3	11
9	0.3	3.7	2.4	0.7	2.3	0.8	1.0	0.7	11.9	8
10	1.0	3.1	0.8	1.7	3.9	0.8	0.4	1.9	13.6	6
11	3.3	1.8	2.6	1.7	4.7	1.6	2.1	3.9	21.7	3
12	0	0	0.2	0	0	0.4	1.4	0	2.0	12

A further corroboration was obtained by comparing summations of the shielding factors for the four highest-ranked gages and the four lowest. The four highest-ranked raingages, numbers 9, 10, 11, and 12, had a combined shielding factor of 49. 2, whereas the four lowest-ranked raingages, numbers 3, 4, 5, and 7, had a combined factor of 55. 3.

The results of the investigation of gage exposure variability as a possible cause or explanation for the distribution of precipitation in 1950-1959 have indicated that, except for a few unmeasurable variations, differences in exposures in the urban area probably were not responsible for the observed variations in precipitation. Any shielding differences that did affect the distribution of precipitation were probably most active during snowfall in the winter season. Quantitatively, this effect on snowfall catch could have been 0. 5 inch of water, which accounts for only 12 percent of the 4. 0-inch annual difference in precipitation for the eastern urban area and that for the western urban and rural areas.

A raingage located in an urban area, even with a very unsheltered exposure site, must be considered to have more environmental shielding than most rural raingages, and therefore, the urban raingage will generally catch more precipitation. In larger urban areas it is conceivable that the increased turbulence and friction effects might cause an overall reduction in the speed of storm movement and increase the time required for passage over the city, thereby allowing more precipitation to fall over the urban area.

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Urban Effects. The second possible cause for the maximization of precipitation in the eastern half of the urban area is the influence on precipitation systems from urban effects. These effects are considered to be additional condensation nuclei, additional water vapor, and increased turbulence from surface roughness and thermal heating. In previous descriptions of the data associated with precipitation quantity, seasonal distribution, number of rainy days, number of thunderstorm days, and synoptic conditions, it was indicated that much of these data could be interpreted as indicative of influences from urban effects.

Additional condensation nuclei are presumed to be largely derived from combustion processes. Champaign-Urbana has very few industries and no heavy industries. The five principal point sources of smoke are shown on Figure 1, and none, except for the heating plant near gage 9 and the University heating plant near gage 7, produces any large volume of smoke. Furthermore, the heating plant operations are restricted largely to the colder seasons. The only other potential sources are home heating plants, but only during the cold season. Telford[10] recently stated that industries, other than heavy industries such as steel plants, probably have little influence on the freezing-nuclei count in the atmosphere. Therefore, except for some possible minor influence in the winter season, it is believed that the Champaign-Urbana urban area does not produce sufficient condensation nuclei to have an effect on precipitation systems.

Much the same conclusion can be drawn concerning water vapor production by the Champaign-Urbana urban area. Without heavy industries no great volume of water vapor is released to the atmosphere. The only other possibility for additional water vapor might be evapotranspiration, from urban trees and lawns, which could be greater than that from corn and soybean crops in rural areas; however, data published by Blaney,[14] concerning consumptive water use of plants, which is indicative of the rate of evapotranspiration, indicate that corn and soybeans have a greater combined rate of evapotranspiration than grass and deciduous trees. This indicates that the foliage in the urban area would release less water vapor through evapotranspiration than foliage in rural areas.

It thus appears that air turbulence produced by the Champaign-Urbana urban area could be the only major effect which could influence precipitation. Unfortunately, no measurements of the roughness effect on turbulence are available, but this effect may be considerable, especially when the flat, featureless surrounding rural area is taken into consideration. Thermal heating over the cities also could produce turbulence by lifting the air.

In a recent article DeMarrais[15] has shown that air over an urban area, because of local temperature conditions, is relatively less stable throughout the day than air over rural areas.

A comparison of the mean monthly minimum and maximum temperatures, based on 6 years of comparative data, has shown that the maximum values at the rural Airport station (Figure 1) range from 0.5°, in the summer-fall period, to 1.3° in the winter-spring period, lower than those at the urban Central station.[16] The rural mean monthly minimum temperatures vary from 0.8°, in summer, to 2.0°, in winter, lower than the urban values. This proves that on the average the urban area is warmer than the rural area.

To further examine the urban-rural temperature difference in time and space, two additional weather stations were installed on the fringes of the urban area (Figure 1) for a 12-month period beginning in July 1959. The 2-hourly mean seasonal values from each of the stations were compared with those from the Central urban station, and the results are given in Table 11. Space does not permit a thorough discussion of all the many interesting features displayed in Table 11; however, a few pertinent observations require mention. In all four seasons there are times of the day when the rural (Airport) and outlying urban stations (NW and SE) have temperatures exceeding those at the urban Central station. The time of day when these excesses occur varies from late in the afternoon in winter and fall to mid-morning in spring and summer. The more rapid afternoon cooling at the Central urban station in winter and fall suggests the occurrence of greater radiational heat loss over the urban area.

For each season data in Table 5 were used to select the 8-hour periods of maximum precipitation associated with the precipitation periods which maximized in the eastern half of the cities, and these periods have been indicated in Table 11. Comparison of these 8-hour periods with the mean temperatures of the Central urban station in each season reveals that the period, except in summer, occurred during or just after the hours of maximum heating. Further, comparison of these 8-hour periods with the temperature departures of the rural and outlying urban stations reveals that the 8-hour period in each season always began at hours when the temperature departures began to exceed the Central station mean values. From these relationships it would appear reasonable to conclude that the urban area, because of higher temperatures and greater radiation at the ground surface than in the rural areas, may have been producing more thermal lifting of air and a generally more unstable lower atmosphere, and consequently was affecting precipitation systems. DeMarrais[15] has shown, however, that urban and rural air

COMPARISON OF TEMPERATURES BETWEEN CENTRAL AND FRINGE STATIONS
July 1959-June 1960

Time, CST

	00	02	04	06	08	10	12	14	16	18	20	22	Average
Winter													
Central mean	28.8	28.2	27.8	27.6	28.7	31.5	33.8	34.3	33.1	31.2	30.2	28.9	30.3
Station departures													
SE	-0.3	-0.1	-0.3	-0.4	-1.2	-1.2	-0.6	-0.1	+0.4	+0.1	-0.2	-0.2	-0.3
NW	-0.5	-0.3	-0.4	-0.4	-1.3	-1.1	-1.0	+0.3	+0.7	+0	-0.4	-0.1	-0.4
AP	-1.-	-1.0	-1.6	-1.1	-2.0	-0.6	-0.4	+0.2	+0.4	-0.6	-1.0	-1.4	-0.7
8-hour period of most frequent precipitation								X	1400-2200			X	
Spring													
Central mean	42.8	41.4	40.1	39.3	43.2	47.9	50.8	52.6	52.8	51.0	47.8	45.1	46.2
Station departures													
SE	(Missing)												
NW	-1.1	-1.0	-0.7	-0.9	-0.1	+0.4	+0.4	+0.2	+0	-0.7	-1.6	-1.2	-0.3
AP	-2.6	-2.5	-2.5	-1.3	-0.2	+0.5	+0.2	-0.3	-0.8	-1.7	-2.7	-2.4	-1.3
8-hour period of most frequent precipitation						X	1000-1800			X			
Summer													
Central mean	68.2	66.5	65.3	65.9	70.8	76.4	79.5	81.1	80.9	78.4	74.1	70.3	73.1
Station departures													
SE	-0.7	-0.7	-1.2	-0.8	+1.8	+1.3	+1.3	+2.2	+1.4	+0.9	-1.1	-0.8	+0.3
NW	-0.2	-0.5	-0.5	-1.5	-0.6	-0.3	+0.6	+0.7	+0.8	+1.0	-0.1	-0.2	-0.1
AP	-1.7	-1.5	-1.9	-0.4	+2.1	+1.3	+1.0	+0.1	-0.4	-0.3	-2.4	-1.9	-0.3
8-hour period of most frequent precipitation					X	0800-1600			X				
Fall													
Central mean	47.1	46.3	45.6	46.8	50.6	55.3	58.3	58.7	56.4	52.4	49.7	48.0	51.3
Station departures													
SE	+0.4	+0.1	-0.2	-1.9	-1.2	-0.9	+0	+1.0	+2.1	+1.3	+0.3	+0.1	+0.3
NW	+0.7	+0.2	+0	-2.1	-2.4	-2.0	-0.8	+1.1	+2.4	+2.4	+1.0	+0.8	+0.3
AP	-0.5	-0.7	-1.1	-2.9	-1.8	-0.8	+0	+1.0	+2.1	+0.7	-0.2	-0.5	-0.4
8-hour period of most frequent precipitation						X	1000-1800			X			

temperatures several hundred feet above the surface are not too dissimilar in daylight hours, the period when precipitation maximization in the east was most frequent. DeMarrais also indicated that the urban influence on air temperature above a city was greatest at night, tending to break down the inversion which remains over the rural areas. Thus, his findings tend to refute the claim that thermal effects were a major urban influence on precipitation.

Natural Variability of Precipitation The third possible cause for the precipitation distribution in the Champaign-Urbana area in the 1950-1959 period could be natural spatial variations in precipitation. In this area nearly 40 percent of the average annual precipitation is derived from thunderstorms,[9] and the ex- extreme variability of storm and monthly precipitation in the area is well known.[17] Unfortunately, similar statistical measures of the spatial variability of seasonal and annual precipitation, especially over short distances, are not yet available. Therefore, it is difficult to evaluate statistically the 1950-1959 Champaign-Urbana seasonal and annual patterns in regard to significant differences which may have arisen from natural rainfall variability.

During this same 10-year period the Illinois State Water Survey operated another raingage network in a completely rural area 55 miles northwest of Champaign-Urbana.[17] This network, the Panther Creek Network, was comprised of nine recording raingages located in a 100-square-mile area, as shown in Figure 6.

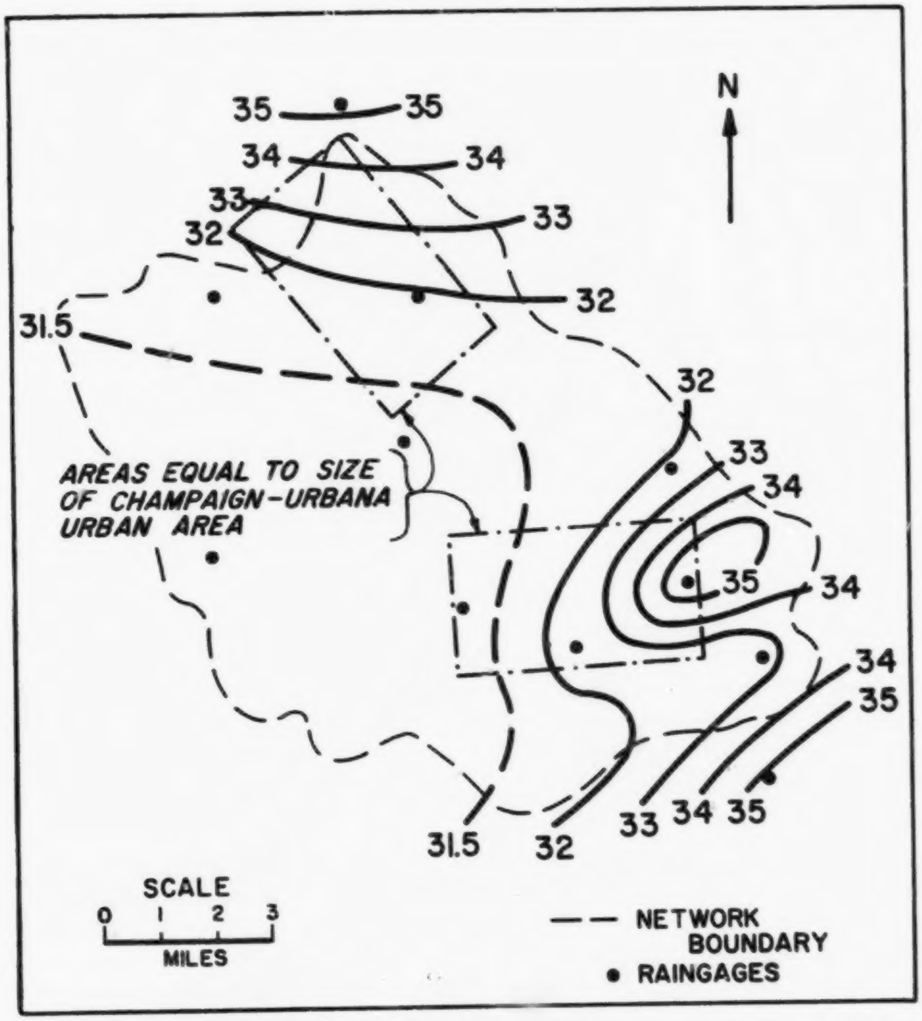
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Figure 6. Annual average precipitation on Panther Creek raingage network, 1950-59

In the results here reported for this network, data from two Weather Bureau raingages located on the periphery of this network were incorporated. The precipitation data from this network are considered to be representative of natural variations in precipitation, and the network is near enough to Champaign-Urbana to experience comparable climatological conditions. Therefore, data from this rural network were compared with that from the urban area, even though the gage densities differed, because the rural network data were the only available expression of natural variability of precipitation for this 10-year period and this area.

The average annual pattern of precipitation in the rural network is shown in Figure 6. Superimposed on this pattern are two rectangles, each the size of the Champaign-Urbana urban area. These rectangles have been placed in two portions of the rural pattern where variations were comparable with those exhibited in the urban network. This indicated that the annual urban pattern (Figure 2) could be entirely a result of natural causes.

The rural network data for each year and each gage were ranked from high to low, as were the urban annual data shown in Table 1. In the rural network, 20 of the 30 possible highest three ranks were achieved by the five easternmost gages. This is comparable with the value of 25 of 30 three highest ranks obtained in the urban area by the six easternmost gages. If the six northeasternmost gages in the rural network are chosen as a group for a similar comparison, we find that these gages had 24 of the 30 highest three ranks. These findings also suggest that the urban precipitation distribution was of a magnitude exhibited by natural variation. In 8 of the 10 years the annual totals of the three easternmost gages in the rural network ranked first. In the urban area the highest annual rank occurred at one of the six easternmost gages in 9 of the 10 years.

The seasonal patterns in the rural network did not show the consistent maximization in the eastern area in each season that was seen in the urban network. In the rural network definite seasonal maximums occurred in the eastern area only in the fall and spring. In the winter a north-south latitudinal increase was apparent; in the summer the precipitation pattern was more ambiguous, and no definite regional maximization occurred. These findings, especially for the winter season, reflect the fact that the rural network was experiencing true natural variations in precipitation. In this climatic region, the distribution of precipitation in winter is much less variable than in the other seasons and also is related closely to change in latitude.

Another measure of rural or natural precipitation variability was made using the data from the individual precipitation periods in the 1958-1959 period. As shown in Table 4, 33 percent of all 1958-1959 precipitation periods in the urban network maximized in the eastern half of the urban area. To obtain comparable values from the larger rural network, it was decided to determine how many of the 245 precipitation periods on the rural network maximized at any one of the three easternmost gages. In the 2-year period, 122 precipitation periods maximized at these three gages. This frequency, expressed as a percent of the total periods, was almost 50 percent, compared with the 33 percent frequency in the urban area. This comparison may be questionable because of differences in area, but it does indicate that a frequent concentration of storm precipitation can occur naturally in a very small portion of a given area. Time did not permit further detailed investigation of the precipitation data from the rural network, but the results presented here appear to prove that most of the urban measurements of precipitation could have been entirely a result of natural variations rather than of any urban influence.

SUMMARY AND SUGGESTIONS

In reporting on a study of precipitation in a moderate-sized urban area with very little industry and no pollution problem, attempts have been made to illustrate some of the important problems associated with the overall question of whether urban effects influence the spatial distribution of precipitation. It might be argued that some of the problems raised by the Champaign-Urbana site would not be applicable in larger cities. Similar data from a larger urban area probably would not provide more enlightening answers, however, because urban-rural percentage differences in precipitation conditions measured in Champaign-Urbana were comparable to those measured at other much larger urban areas.

As stated previously, the present general lack of knowledge of the microscale atmospheric processes does not permit the evaluation and measurement of urban effects on precipitation processes with the degree of accuracy desired. In general, these effects have been claimed to produce increases in precipitation on the order of 5 to 15 percent, but meteorologists cannot presently measure or describe the atmospheric processes well enough to achieve a high degree of accuracy in theoretical calculations.

The only other hope for defining the relation between urban conditions and precipitation is through an intensive measurement program to be used with generalized inferences. The results of the Champaign-Urbana study have shown that the precipitation maximization in Urbana could easily be claimed to result either from urban effects or from natural variations of precipitation. Raingage exposures presented a problem in the evaluation of effects; and admittedly, not all of the instruments and data needed to make such decisions were available. To instrument an urban area for the purpose of evaluating urban influences on precipitation would be a difficult and tremendously expensive project, and investigators would want to be confident that results from such an undertaking would provide reliable answers. Another and probably more serious problem to overcome, even with a thoroughly instrumented project, is that of natural variation of precipitation, especially in climatic regions where variability is known to be excessive because of the predominance of shower-type rainfall. Much more statistical information is needed concerning the variability of seasonal and annual precipitation in small densely-gaged networks. Until these data are available one cannot provide a statistical description of the natural spatial variability of precipitation; and until this description is available, it will be difficult to evaluate the natural variability of precipitation in a study of the relationship between urban influences and precipitation. Many large urban areas in the United States are near to physical features, such as large water bodies, hills, and mountains, which make urban-precipitation studies even more difficult.

Whether a given city produces, or can produce, a 5, 10, or 15 percent increase in rainfall and number of rainy days in portions of its urban area is a question that neither meteorology nor climatology can at present answer accurately. Gross or generalized urban effects may be claimed, but to obtain reliable evidence of their existence, we must increase our knowledge of atmospheric processes and undertake extensive measurement programs.

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DISCUSSION

CHAIRMAN LANDSBERG: This was certainly very gracious of Mr. Stout to present Mr. Changnon's paper. If Mr. Stout is willing to stand in for his colleague, we have a minute or two for questions.

DR. SCHMIDT: One thing occurs to me in regards to this. Due consideration has been shown to the individual exposure of the stations, but I wonder if there isn't some possibility that the urban area, the built-up area itself, creates to a general decrease in the low-level wind flow in that region. Would it be possible that the lighter winds in the eastern region might result in a larger apparent catch of precipitation? The rain gages are so sensitive to wind speeds that if the mean winds in that region were generally lower, it is a possible thing that I think you could look into fairly easily. Because if it is so, then the catch would be most different during higher winds and less different during low winds.

MR. STOUT: This is true. We are all aware of this, but as yet we have no data with which to correct for this apparent defect. But I think you are right that the general wind movement is much less in the built-up areas than in the rural areas, or at the outer fringes of town.

FROM THE FLOOR: Is your Panther Creek network totally free of urban influence?

MR. STOUT: Yes.

FROM THE FLOOR: So the variations that you found here which are equal in magnitude to the urban area could not in any way be charged to wind speed?

MR. STOUT: The topmost gage was in a town of about 750 or a thousand people, and there were no industries there. But over to the right there that was all rural areas, all open country and no problem as far as exposures.

DR. HEWSON: Are there any other orographic effects other than the Panther Creek?

MR. STOUT: No, the change in elevation at Panther Creek is a maximum of about 100 feet in that area, so it is a relatively flat land.

Some Effects of Air Pollution on Visibility in and Near Cities*

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Summary

Regularly obtained visibility observations are examined with regard to effects due to nearby air pollution sources. Some inherent difficulties in dealing with visibility data are pointed out. The effects on visibility of wind speed and of wind direction relative to pollution sources are described. A method is presented for analyzing possible trends in visibility.

One of the more profound effects of air pollution is on visibility. To some extent such effects are experienced by most members of a community and therefore are worthy of consideration in air pollution appraisals. To obtain a record of visibility observations suitable for study, one turns almost invariably to the nearest observing office of the Weather Bureau. Typically, such offices are at the airport, often near the outskirts of the city. Observations at the edge of a city offer an opportunity to assess the effects of the urban area as a general pollution source. As shown in Figure 1, the urban area of Sacramento, California, acts as a source of pollutants that reduce the visibility at the municipal airport, located 4.5 miles south of downtown Sacramento. Relative to the airport, most of the Sacramento urban area lies in the sector northwest clockwise through east-southeast. As the drawing indicates, the higher percentages of poor visibilities, 0-10 miles, are associated with winds from the urban directions.

The data in Figure 1 are based on hourly observations during May, July, September, and November for 18 years. Only daytime observations have been considered, since visibility during darkness depends on different factors and is considered less reliable. In an attempt to eliminate visibility reduction due to natural causes, the observations considered were restricted to periods in which wind speeds were 1 to 10 miles per hour (mph), no precipitation was occurring, and relative humidity was less than 90 percent. Even with these restrictions, there remain 13,726 observations. For small samples such visibility wind roses are often less regular than that shown in Figure 1.

In this analysis the implied assumption is that the wind direction at the time of the visibility observation is roughly

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*This work is supported by the U. S. Public Health Service.

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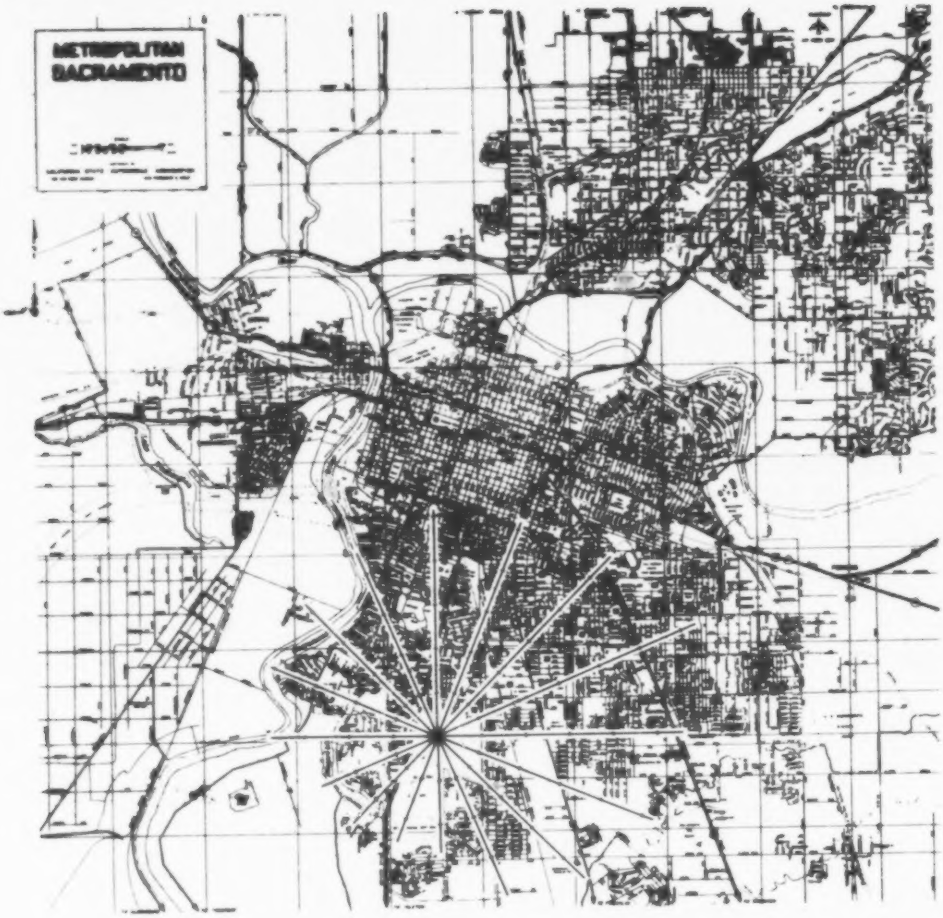

Figure 1. Sacramento metropolitan area with wind rose of the percent frequency for each wind direction for visibilities of 0-10 miles. Wind rose centered on observation site, municipal airport. Data based on daytime hourly observations during May, July, September, and November for 18 years. Observations with precipitation and/or relative humidity greater than 70 percent, or with wind speeds other than 1-10 mph omitted.

representative of the trajectory of the air since it passed over significant pollutant sources. This assumption appears valid at Sacramento but may not apply in areas of small-scale eddies or where there are marked diurnal variations in air flow.

The diurnal variation in visibility at Chicago's Midway Airport from January to March 1930 was discussed by Weck.[1] He observed that the main contribution to reduced visibility was smoke. An average daily minimum visibility of 3.0 miles at 8:00 a.m. was attributed to the smoke released after the man of the house arose and stoked the furnace. As the day advanced, the smoke became lighter (probably in part because of increased atmospheric mixing) and the visibility improved to 4.5 miles near 3:00 p.m. In the late afternoon firing at residences and banking of factory furnaces reduced the visibility to a secondary minimum of 3.5 miles near 5:00 to 6:00 p.m., after which it slowly rose again to an average daily maximum of 7.0 miles at 4:00 a.m.

At Columbus, Ohio, daily visibility observations made at the center of the city at 8:00 a.m. for 11 years have been compared to corresponding Weather Bureau observations at the airport, about 6 miles to the east-northeast. The airport is well beyond the city limits and is considered an out-of-town location. Figure 2 shows that the average annual visibility at the city location is consistently about 1 mile lower than that at the airport. No observations were included if precipitation was occurring. It is interesting to note in these data a trend of improving visibility through 1958 at both sites. This trend may be related to the average annual dustfall rates in Columbus, shown in Figure 2. The steady decline in these rates is consistent with the trend of increasing visibility, and both trends reflect the effective program of the Division of Smoke Regulation and Inspection of the Columbus Department of Public Safety.

The term "visibility" is used in this paper in its meteorological sense, which is more properly "visual range," or the greatest distance at which prominent objects can just be seen. This use should be distinguished from visibility in terms of the clarity with which objects can be seen, although the two uses are not unrelated.

An important use of visibility data is as an indicator of air pollution trends, as described for Columbus. To determine the visibility trend for the United States in general the percent frequencies of all hourly visibilities less than 7 miles (due to all causes) have been compared at a number of locations for two periods separated by about 15 to 20 years. The data are presented in Table 1.

TABLE 1

PER CENT FREQUENCIES OF ALL VISIBILITIES LESS THAN 7 MILES AT WEATHER BUREAU AIRPORT STATIONS[a]

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
BAKERSFIELD	1/29-12/38	23	9	3	0	1	1	2	3	7	8	11	29
CALIFORNIA	7/55-6/59	47	29	6	5	2	3	2	5	9	15	40	58
BURBANK	10/31-12/38	18	24	24	29	32	48	43	42	43	38	22	21
CALIFORNIA	5/50-4/55	25	14	21	32	37	42	45	51	51	47	34	26
CARIBOU	1/38-12/41	36	30	24	19	15	16	18	16	19	20	31	39
MAINE	7/59-3/61	21	30	28	21	13	14	10	13	10	14	23	18
CHICAGO	1/30-12/38	72	70	65	62	54	48	47	52	52	58	56	73
ILLINOIS	1/59-12/60	57	37	48	32	34	30	32	38	33	40	29	39
COLUMBIA	6/30-12/38	31	34	29	22	12	7	4	8	13	18	23	36
MISSOURI	7/59-3/61	21	28	24	4	2	6	6	4	2	14	5	15
COLUMBUS	1/30-12/38	63	57	45	28	19	16	16	23	23	35	53	68
OHIO	7/58-6/61	46	37	29	19	16	20	26	32	24	25	23	41
DES MOINES	4/33-12/38	54	46	41	29	21	14	9	20	20	26	32	52
IOWA	7/58-6/61	23	30	28	11	9	9	10	8	9	12	11	17
EL PASO	7/30-12/38	3	5	9	10	4	2	1	0	2	1	1	3
TEXAS	1/49-12/53	4	4	4	4	2	1	1	0	1	1	1	3
GRAND ISLAND	9/31-12/38	25	23	20	23	13	4	3	8	10	10	15	20
NEBRASKA	7/58-6/61	15	23	20	10	10	5	3	2	5	3	6	9
GREENSBORO	1/30-12/38	31	24	23	18	10	6	10	11	16	15	26	34
N. CAROLINA	7/58-6/61	23	24	19	11	12	17	22	28	22	24	14	13
INDIANAPOLIS	7/29-12/38	61	56	50	38	26	18	19	31	32	38	46	65
INDIANA	7/58-6/61	35	40	33	14	14	18	22	30	19	21	18	31
LAKE CHARLES	3/39-4/42	11	12	17	11	6	3	3	5	6	12	11	19
LOUISIANA	7/59-3/61	20	24	16	9	3	4	8	10	9	15	15	20
MEDFORD	7/29-12/38	35	12	5	4	2	1	3	2	9	13	23	37
OREGON	8/50-7/55	40	23	4	5	2	0	1	3	5	29	49	46
MILWAUKEE	1/30-12/38	50	45	40	34	32	27	22	30	32	38	36	43
WISCONSIN	7/58-6/61	29	30	28	17	18	11	11	22	12	19	18	21
MOLINE	1/30-12/38	63	55	51	40	25	21	18	37	35	45	51	66
ILLINOIS	7/58-6/61	31	34	34	14	11	14	20	19	14	21	12	26
NASHVILLE	7/37-12/41	45	41	32	11	10	8	13	16	12	23	43	44
TENNESSEE	7/58-6/61	26	27	17	9	7	10	15	17	17	19	16	25
OAKLAND	7/29-12/38	26	19	9	4	2	3	7	11	25	28	41	30
CALIFORNIA	5/50-4/55	28	26	8	9	8	5	11	10	18	27	37	30
PEORIA	3/36-12/38	68	56	40	29	20	16	17	28	30	37	41	62
ILLINOIS	7/58-6/61	36	36	33	12	11	11	16	20	12	20	17	26
RICHMOND	6/29-12/38	39	33	27	22	19	18	20	22	26	26	34	38
VIRGINIA	7/58-6/61	22	24	20	13	18	22	26	41	27	23	18	18

TABLE 1 (Continued)

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
SACRAMENTO	1/30-12/38	42	22	9	4	2	1	1	2	13	16	37	55
CALIFORNIA	3/50-2/55	39	30	9	9	3	2	4	4	8	19	44	46
SALEM	1/34-12/38	35	29	15	6	2	3	6	11	35	51	46	37
OREGON	7/55-6/59	25	19	9	3	3	1	1	1	10	24	27	35
SAN DIEGO	1/30-12/38	90	85	86	92	91	87	88	87	81	77	86	88
CALIFORNIA	8/49-7/54	79	78	88	82	88	86	81	75	67	71	73	82
SEATTLE	1/30-12/38	38	36	19	16	8	8	10	30	44	53	46	36
WASHINGTON	7/55-6/59	24	27	13	10	7	6	10	13	28	34	38	28
SIOUX CITY	1/47-12/51	16	20	17	10	5	7	3	7	4	7	11	17
IOWA	7/58-6/61	22	24	25	8	8	5	4	4	5	6	9	11
SOUTH BEND	6/30-12/38	65	56	51	33	21	18	14	20	24	37	45	67
INDIANA	7/58-6/61	51	49	37	21	13	15	21	23	20	24	27	41
ST. LOUIS	1/35-12/41	50	45	39	32	18	14	14	17	22	33	40	52
MISSOURI	1/58-12/60	34	18	28	10	12	8	13	11	9	20	13	22
TULSA	3/30-12/36	26	24	17	16	7	3	2	4	6	11	14	22
OKLAHOMA	7/58-6/61	14	19	12	2	3	5	3	2	6	8	4	12
WINSLOW	2/31-12/38	3	2	2	2	0	0	0	0	0	0	0	4
ARIZONA	7/55-6/59	3	2	2	1	0	0	0	0	00	2	1	0

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[a] Observations at hourly intervals.

Data Sources: U. S. Weather Bureau Local Climatological Data, Climatography of the U. S. No. 30-(for selected stations), and Normal Flying Weather for the U. S. (New Orleans, 1945).

The stations listed in the table were selected because the observation sites did not change significantly during the time between the two periods compared. Where the frequency of visibilities less than 7 miles is greater in the later period (lower row) than in the earlier period (upper row), the figures are boxed in. Low visibilities are more frequent in the later period in less than 26 percent of the comparisons. Further, these increases in poor visibility are for the most part rather small: of the 336 comparisons only 13 are greater than 10 percent, 4 are greater than 20 percent, and none are greater than 30 percent. On the other hand, many of the decreases in frequency of low visibilities are large. 108 are greater than 10 percent, 35 are greater than 20 percent, and 10 are greater than 30 percent. These changes are all the more significant in view of a revised method of reporting visibility. As pointed out by Robinson [2*] visibility was reported before January 1, 1939, as the greatest visibility over the horizon. Since then it has been reported as the lowest visibility over the half of the horizon (not necessarily continuous) with the

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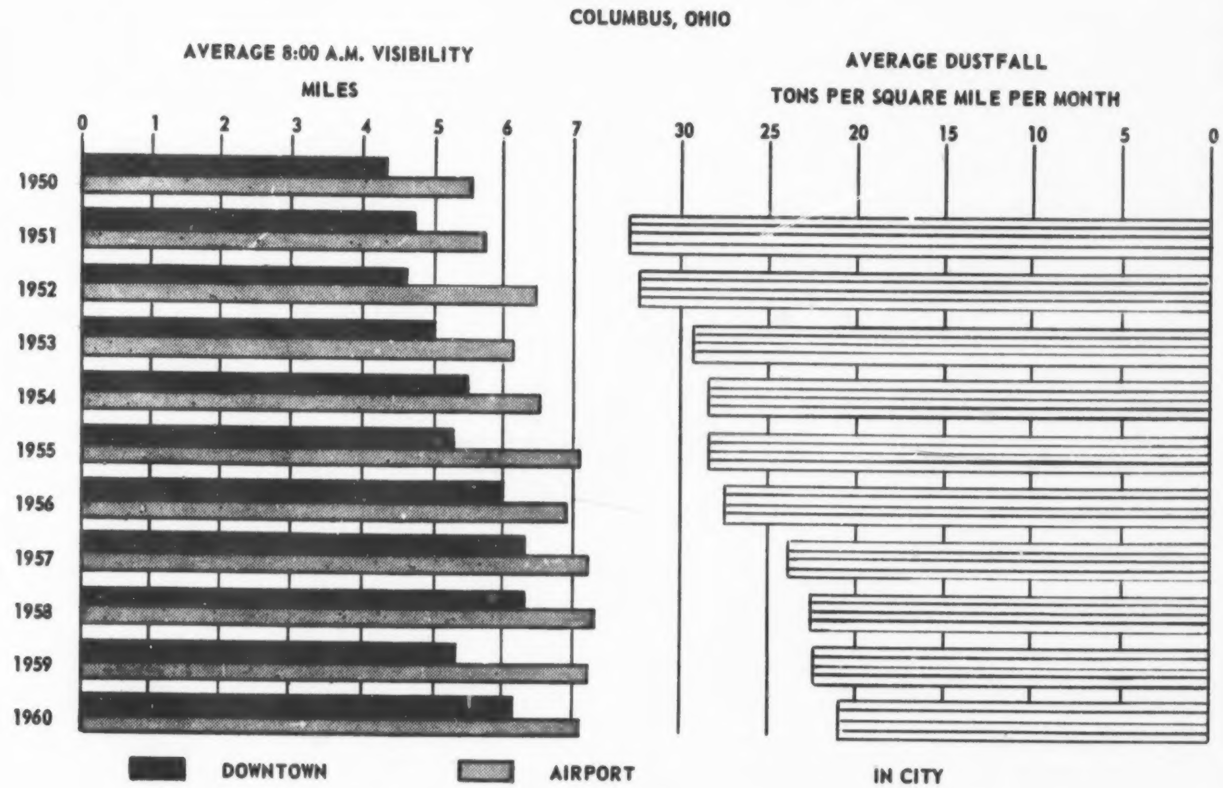
*This reference includes an excellent discussion of the theory of visibility and many of the practical considerations to be made in utilizing visibility data for air pollution purposes.



DATA SOURCE: COLUMBUS DIVISION OF SMOKE REGULATION AND INSPECTION 14

Figure 2. Average 8:00 A.M. visibility at downtown Columbus, Ohio, and at the municipal airport, 6 miles east-northeast; and average dustfall rates in Columbus.

greatest visibility.

Although the data of Table 1 are meager, the differences seem much too large to attribute to chance alone. It appears that visibility in many urban areas of the United States is improving. Such a trend is perhaps surprising, but there is some evidence to indicate that it is real. Prior to control of the quality of solid fuel in St. Louis (beginning about 1941) and in Pittsburgh (beginning about 1945) pollution in winter, due largely to smoke from coal combustion, was often dense enough to require the use of street lamps and automobile headlights at midday. It has been estimated that in St. Louis smoke was reduced 75 percent and in Pittsburgh, 70 percent.[3] Visibility data for St. Louis, included in Table 1, show a marked reduction in poor visibilities, especially in the colder months.

Some idea of the contaminants produced by the combustion of coal, oil, and natural gas may be obtained from Table 2. The weight of particulate material produced per BTU decreases by about an order of magnitude for each conversion, from coal to oil and from oil to gas. Coal and oil combustion produce about the same quantity of gaseous material, but natural gas produces only one-fifth that amount.

TABLE 2

COMPARISON OF CONTAMINANTS FROM
COMBUSTION OF COAL, OIL AND
AND NATURAL GAS (INDUSTRIAL BOILERS)[a]
($lb/10^7$ Btu)

	Coal	Oil	Gas
Particulates	14.1	1.93	0.14
Gases	26.8	26.62	5.24
Total	40.9	28.55	5.38

[a] After Neiburger (Ref. 15)

A specific example of the effect of fuel conversion on visibility improvement has been described by Bloodworth.[4] At the municipal airport at Atlanta, Georgia, a railroad switching yard 2 miles to the northwest was listed as a principal smoke source (for reduced visibilities).[5] The total number of regular hourly observations when smoke alone reduced the visibility to less than

1 mile was tabulated for the period from 1944 to 1951. Table 3 shows that as the locomotives in the yard were converted from steam (coal) to diesel, the annual number of poor visibilities due to smoke alone was greatly reduced. This effect was most pronounced during the period from 1947 to 1949. Thereafter the continued conversion of locomotives to diesel fuel had little apparent effect. Bloodworth noted in addition that smoke reduction at the airport was also augmented by a general fuel change in the area from coal to natural gas.

TABLE 3

TOTAL NUMBER OF VISIBILITY OBSERVATIONS
IN GIVEN VISIBILITY CATEGORIES DUE TO SMOKE ALONE
AT ATLANTA MUNICIPAL AIRPORT, GEORGIA[a]

	Visibility Less Than		Percent Conversion of Steam (Coal) to Diesel Locomotives in Nearby Yards
	1 mile	3 miles	
1944	17	191	
1945	20	182	
1946	17	135	Started
1947	15	139	20
1948	5	113	
1949	1	17	60
1950	0	6	
1951	2	22	90

[a] After Bloodworth (Ref. 4)

Nearby railroad yards have been listed as a common primary source of smoke and reduced visibility at many airports.[5] The American Petroleum Institute[6] reports that before World War II less than 2 percent of the locomotives in use on the major railroads burned diesel fuel. In 1958 more than 90 percent of such locomotives were diesel fueled.

Besides the changing of fuels there have been improvements in combustion techniques and equipment and in the methods of capturing pollutants before they are emitted to the atmosphere. The general public is certainly becoming more aware of air pollution, with the result that increasing efforts are being made to reduce emissions to the atmosphere.

It is not intended here to settle the matter of whether visibility in the United States has been generally improving or deteriorating. Several significant matters have not even been mentioned. But the information presented here suggests that the emission of visibility-reducing materials to the atmosphere well may have declined.

For specific locations the evaluation of visibility data with reference to air pollution is not often simple. In such studies it is desirable to eliminate those cases of visibility reduction due to natural causes. For precipitation this is straightforward. For fog it is much less so because many man-made pollutants are hygroscopic and may act as condensation nuclei in the formation of fog. Further the meteorological conditions favorable to fog formation are also conducive to poor dispersion of air pollutants. The usual procedure for eliminating cases of poor visibility due to natural causes is to select some relative humidity above which the visibility observations are neglected. In trend studies it would be helpful if the dispersive characteristics of the atmosphere and their effects on production of pollutants would not vary from year to year. But they do vary, and there are seldom sufficient data to allow for such effects.

In addition to the troublesome influences of the weather there are other difficulties in dealing with visibility data. Since visibility is defined as the greatest distance at which objects can just be seen, there must be objects present. In some localities the number and distribution of objects, or markers, may be unsatisfactory. Also, the erection of new markers may change the spectrum of reported visibilities. Visibility observations are subjective estimates made by trained and experienced observors. These estimates are based on the ability to "see" and it is known that such capacities are far from constant, either among different people or in the same person at different times.

Although not all of the factors influencing visibility have been touched on, it should be apparent that there are good reasons for visibilities to fluctuate markedly from year to year (and over even shorter spans). In trend studies such variations are often observed, with the result that the trend is difficult to evaluate, especially over short periods. It is usually reasonable to assume that such fluctuations are random, however.

One of the more extensive studies of the visibility trend relative to air pollution was carried out by Neiburger [7] for downtown Los Angeles for the years 1933 through 1954. From observations at 5:00 a.m., noon, and 5:00 p.m. a great many tabulations of visibility by wind direction, relative humidity, time of day, season, and year were prepared. It was shown that the frequency of very good visibilities decreased markedly as the population and industry of the area grew. After about 1947 to 1948, when the control of pollutants was initiated, visibility seems to have improved in spite of a continued increase of population and industry. Neiburger concluded that these trends were not due to differences in the weather.

Using a similar type of analysis, Robinson, Curie, and James [8] considered noon visibilities at downtown San Francisco for the period 1933 to 1956. They noted that for various visibility ranges the annual frequencies varied from year to year. After restricting the observations to cases of light wind and low relative humidity, they concluded that it was difficult to observe any long-term visibility trend related to air pollution.

Holzworth and Maga [9] have suggested a method for analyzing the trend of visibility. This method, which will be illustrated here, has been applied to data for Sacramento and Bakersfield, California, with the conclusion that the visibility has deteriorated at both cities, supporting the belief that air pollution in California's Central Valley is increasing. The method of Holzworth and Maga was also applied to Neiburger's Los Angeles data, which were extended 5 years through 1959. Before controls were initiated, a trend of rapidly declining visibility was indicated for Los Angeles. After controls there was little trend in the visibility. From a control standpoint this latter is significant in view of a rapid rise in population and the attendant increase in automobile emissions.

The method of trend analysis suggested by Holzworth and Maga will now be illustrated by application to data for the municipal airport at Salt Lake City, Utah. Only hourly daytime observations (about 8:00 a.m. to 5:00 p.m.) during periods with no precipitation and with relative humidities less than 90 percent are considered. The total range of visibility is broken down into a number of sub-ranges, and the percent frequencies of occurrence in each of these ranges is tabulated for each year. The advantage of considering the visibility by ranges rather than using median or mean values is that the changes that occur can be detected more precisely. In the left portion of Figure 3, the percent frequencies of visibilities in the indicated ranges are plotted for October of each year from 1946 to 1960. There are some rather large variations from year to year, but as a whole the linear regression lines, fitted by the method of least squares, depict the general trend in each range fairly well. In this particular case there is a clear trend of improving visibility. The frequencies in the two higher visibility ranges are both increasing, while the frequencies in the three lower ranges are all decreasing.

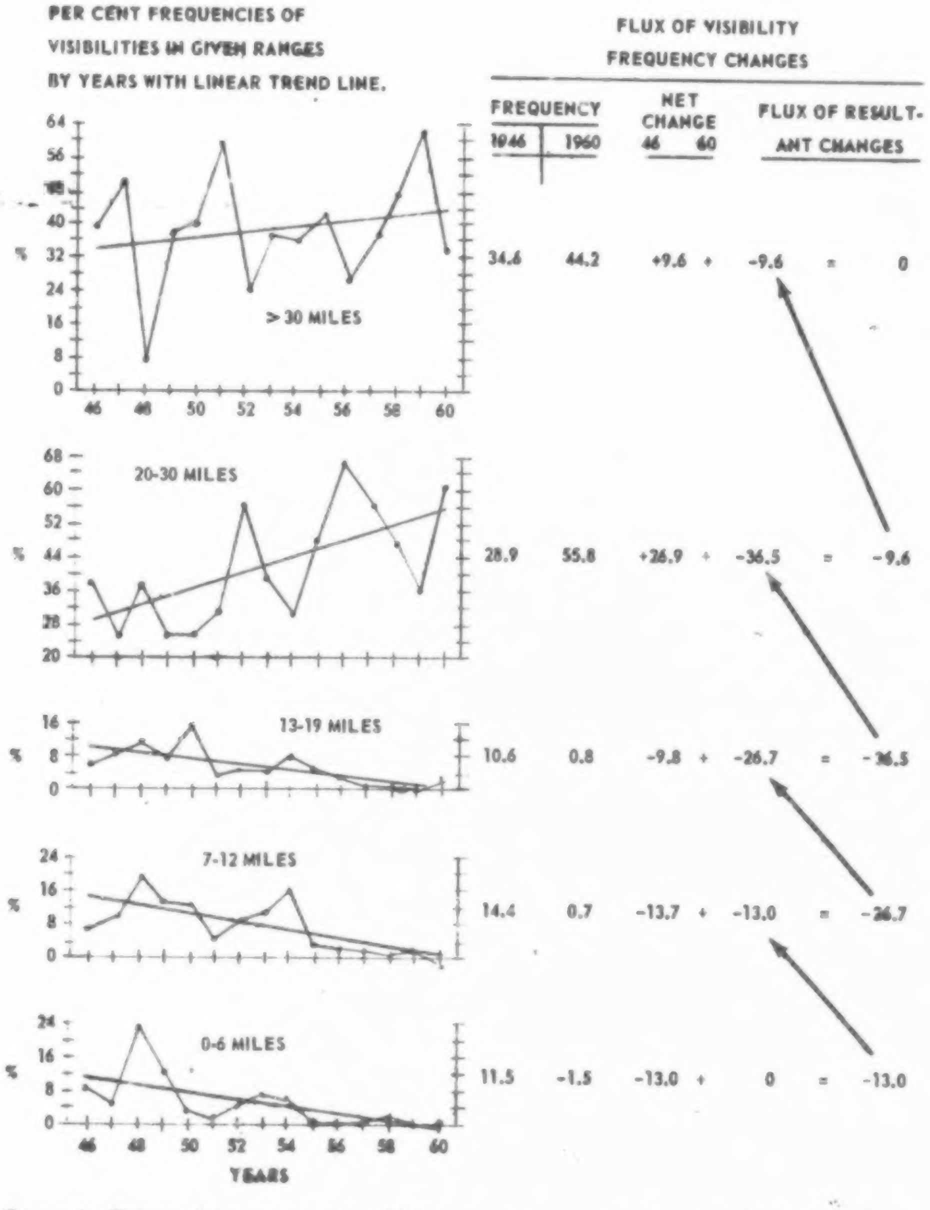


Figure 3. Percent frequencies of visibilities in given ranges by years (left), and schematic shift of visibility frequency changes (right) at Salt Lake Municipal Airport in October. Linear regression lines fitted by method of least squares. Data based on daytime hourly observations; observations with precipitation and/or relative humidity greater than 90 per cent omitted.

But the matter may be pursued further in order to include some numbers in the trend, and this will also be helpful in the evaluation of more complicated trends. For any one year the total frequency of observed visibilities in all ranges is 100 percent; this is true also for the frequencies determined from the linear regression lines. Therefore, the initial and terminal points of the regression lines may be used to obtain the net percentage frequency changes over the span of years considered, as shown in the right portion of Figure 3. For instance, from the regression line the frequency of visibilities in the range greater than 30 miles is 34. 6 percent in 1946 and in 1960 it is 44. 2 percent. The net change is plus 9. 6 percent, and so on for the other ranges. The algebraic sum of the changes in all ranges is zero, and the increases are compensated for by decreases elsewhere.

But now it is important to consider how such compensations are likely to occur. A negative net change represents a surplus of visibilities in that particular range, and a positive change, a deficit. The problem is to determine how the surpluses and deficits in the various visibility ranges interact.

The matter of why the net frequency changes in visibility ranges should interact may be considered from another point of view. If other things are the same, when the concentration of visibility reducing materials changes, a similar effect may be expected on all visibilities that would have occurred otherwise. Let us take the very simplified case of three visibility ranges, low, intermediate, and high, each with frequency of occurrence of 33. 3 percent at some initial time. At some later time if the general concentration of visibility reducing materials is less we may expect, for instance, that 10. 0 percent of the frequencies that would otherwise have been poor are now intermediate, 10 percent of the intermediate are high, and 10 percent of the high are just higher. The result is that at the later time the resulting frequencies are low: 23. 3 percent, intermediate: 33. 3 percent, and high 43. 3 percent. It would appear that the only visibilities affected were those in the upper and lower ranges. But actually there has been a flux of visibilities upward to higher ranges.

Consider a case of the visibility improving, say, from 3 to 25 miles. Such changes are not discontinuous, but the visibility passes continuously through intermediate valves. Correspondingly, with a trend of improving visibility, as in Figure 3, it is expected that the surpluses (net frequency decreases) in the lower visibility ranges are shifting upward to each next higher range. In each case the amount shifted to the adjacent range is algebraically added to the net change there and the resultant value is shifted to the next range. These resultant shifts are indicated by the arrows in the right portion of Figure 3. For instance, in the lowest range, 0 to 6 miles, the net change from 1946 to 1960 is minus 13.0 percent. This surplus is shifted up to the next higher range, 7 to 12 miles, where it is added to the net change there, minus 13.7 percent. The resultant is minus 26.7 percent which is shifted up to the next range, 13 to 19 miles, where the net change is minus 9.8 percent. The resultant change in the 13-to-19 mile range is minus 36.5 percent and this is shifted to the 20-to-30 mile range, where the net change is plus 26.9 percent. The resultant change in the 20-to-30 mile range is minus 9.6 percent, which, when shifted to the highest range, greater than 30 miles, just balances the net change there of plus 9.6 percent. In Figure 3 it is shown that in all cases the resultant shifts (of surplus frequencies) are all upward to higher visibility ranges. The total resultant shift upward is 85.8 percent, and it is clear that there is a marked trend of improving daytime visibility at Salt Lake City in October.

The visibility trend at Salt Lake City was also studied for December; the analysis is shown in Figure 4. Here the major visibility changes are in the two upper ranges; the best visibilities are declining in frequency and the second-best are increasing. As shown on the right side of Figure 4, the total resultant shift downward to lower visibility ranges is 18.0 percent, the total upward to higher ranges is 2.5 percent, and the sum is 15.5 percent downward. Therefore, there is a slight trend of deteriorating visibility in December.

In view of the improving trend in October this is surprising. But a deeper look into the matter will indicate that such opposing trends are not without some basis. In 1941 Salt Lake City passed an air pollution control ordinance, aimed primarily at reducing smoke emissions. It has been stated that emission of particulate matter within Salt Lake City limits has been reduced substantially as a result of enforecement activities.[10] Natural gas was brought to the area about 1941, and steady conversion from coal to gas was responsible for much of the reduction in particulate emissions. It is significant that Salt Lake City is the only municipality in the state having an air pollution control ordinance. As shown in Figure 5, the city is located near the center of a large intermountain valley. This valley is developing rapidly. It is estimated that from 1940 to 1958 the population grew from 347,000 to 632,000.[10]

In October, when there is a trend of improving visibility, space heating is necessary, especially at night. The mean daily maximum temperature for October is 66.5°F and the minimum

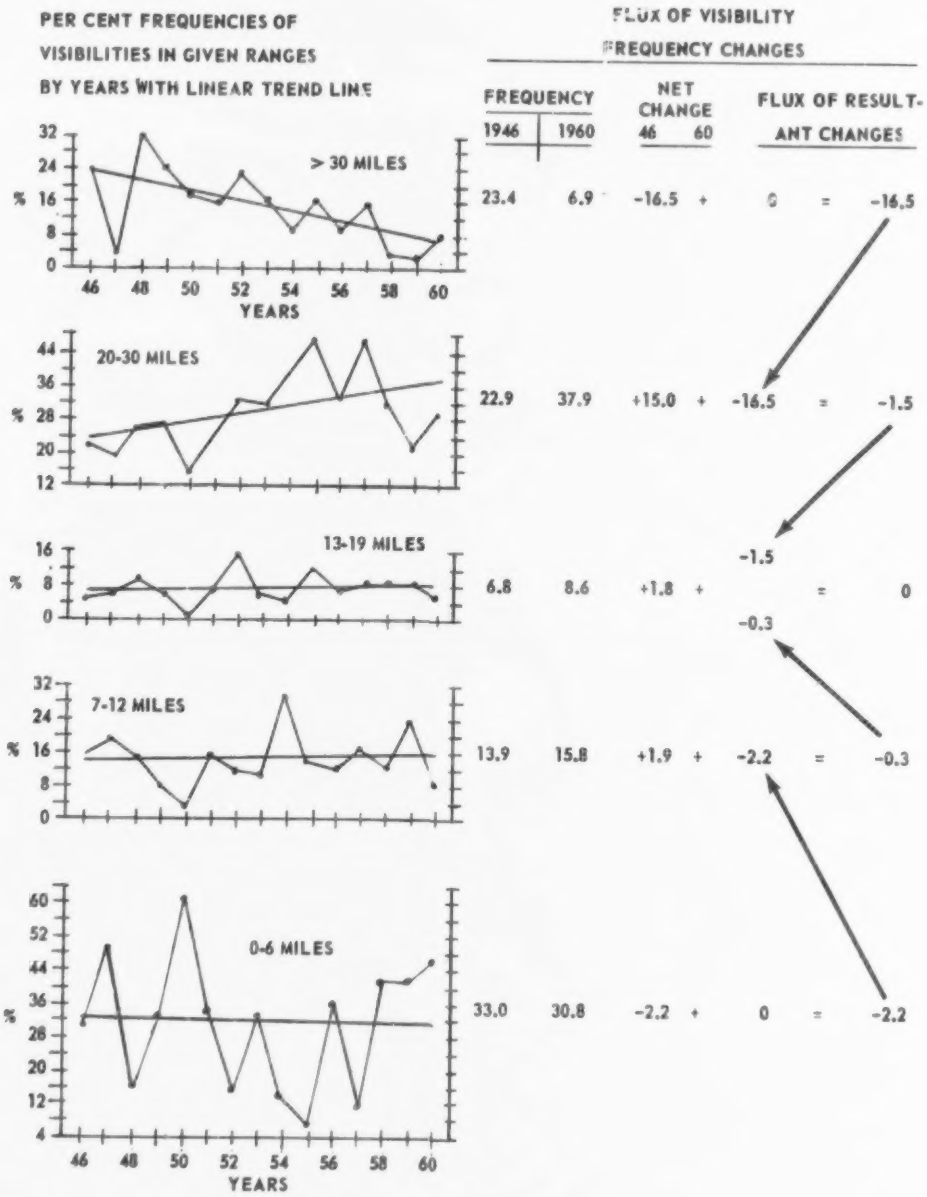


Figure 4. Percent frequencies of visibilities in given ranges by years (left), and schematic shift of visibility frequency changes (right) at Salt Lake Municipal Airport in December. Linear regression lines fitted by method of least squares. Data based on daytime hourly observations; observations with precipitation and/or relative humidity greater than 90 per cent omitted.

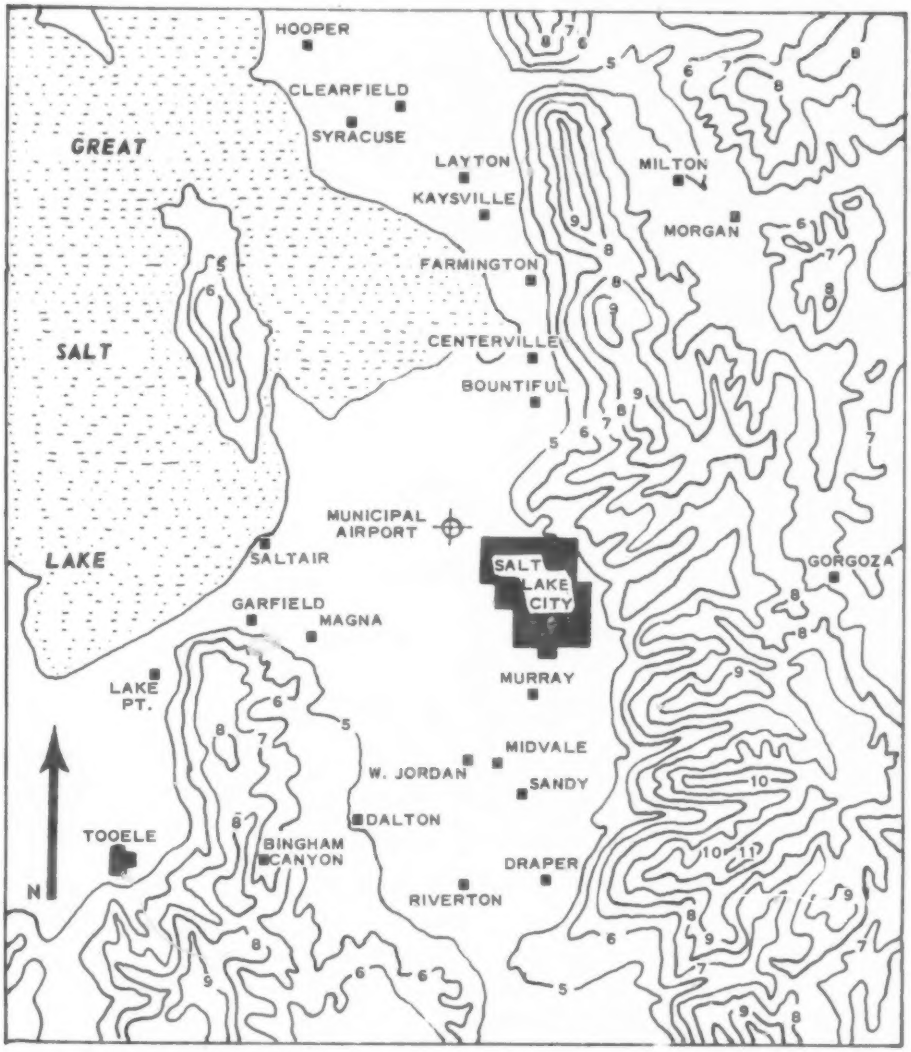

HOOPER
CLEARFIELD
SYRACUSE
GREAT
SALT
LAKE
LAYTON
KAYSVILLE
MILTON
MORGAN
FARMINGTON
CENTERVILLE
BOUNTIFUL
MUNICIPAL AIRPORT
SALTAIR
SALT LAKE CITY
GORGOZA
GARFIELD
MAGNA
LAKE PT.
MURRAY
MIDVALE
W. JORDAN
SANDY
DALTON
TOOELE
BINGHAM CANYON
DRAPER
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Figure 5. Salt Lake Valley, Utah. (Elevation contours in thousands of feet).

is 39.2°F.[11] The dispersive capacity of the atmosphere is much less at night than during the day; low-level temperature inversions are frequent at night,[12] and it is estimated that the mean daily maximum mixing depth is 1000 meters. In the forenoon wind directions are primarily from the city area, south-southeast, and in the afternoon from the lake, northwest. With such a set of conditions a pattern of high pollution concentration in the morning with much lower values during the afternoon is reasonable.

Therefore, pollutants that reach the airport in the morning, before the atmosphere is well-stirred, will be most effective in reducing the visibility. Figure 6 shows the percent frequencies of visibilities of 0 to 12 miles for each wind direction (for wind speed of 1 to 10 mph in October. Poor visibilities are by far most frequent with winds from the direction of Salt Lake City, from the sector east through south. It is clear that Salt Lake City is a direct source of poor visibilities at the airport during October. Recall that in Figure 3 the trend in frequency of visibilities in the ranges 0 to 6 and 7 to 12 miles was downward. The fact that the visibility trend in October is upward reflects the effectiveness of the control program in Salt Lake City.

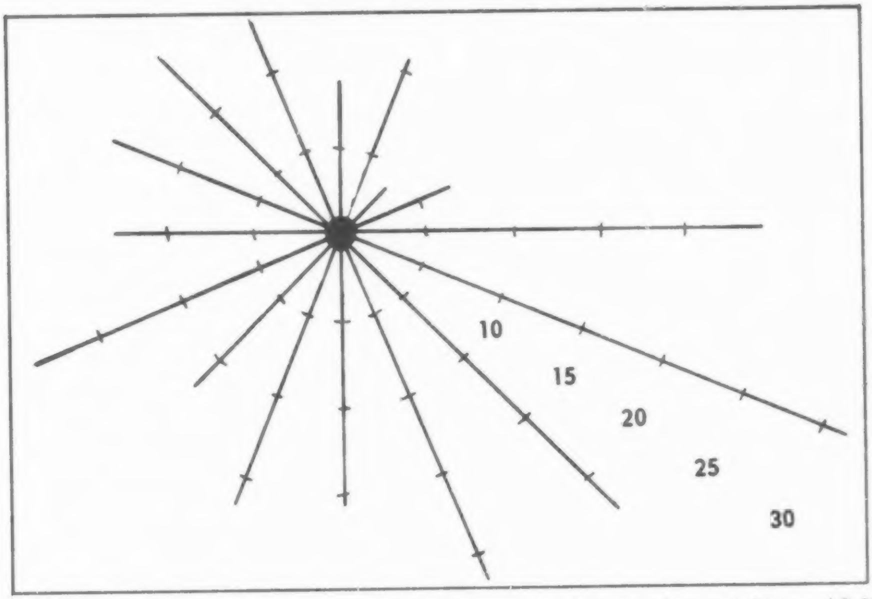

Figure 6. Wind rose of percent frequency for each wind direction for visibilities of 0-12 miles at Salt Lake Municipal Airport in October. Data are the same as in Figure 3 except that only wind speeds of 1-10 mph are considered.

The visibility wind rose for December, shown in Figure 7, is based on the same type of analysis as that in Figure 6. Although visibilities of 0 to 12 miles are most frequent with winds from the northwest, there is no particular sector for which the frequencies are especially greater than for others. Therefore, low visibilities are about as likely from one sector as another. It is concluded, then, that concentrated pollutants are trapped in the valley for several days at a time and simply recirculated. Schmalz[13] has explained such occurrences in association with stagnating anticyclones over Utah, especially in winter. He noted that after about a week of stagnation, smoke (reported by pilots) extended from Salt Lake City to the Nevada State line, 110 miles away. Schmalz also noted the relationship between low visibilities and wind direction, shown in Figure 6.

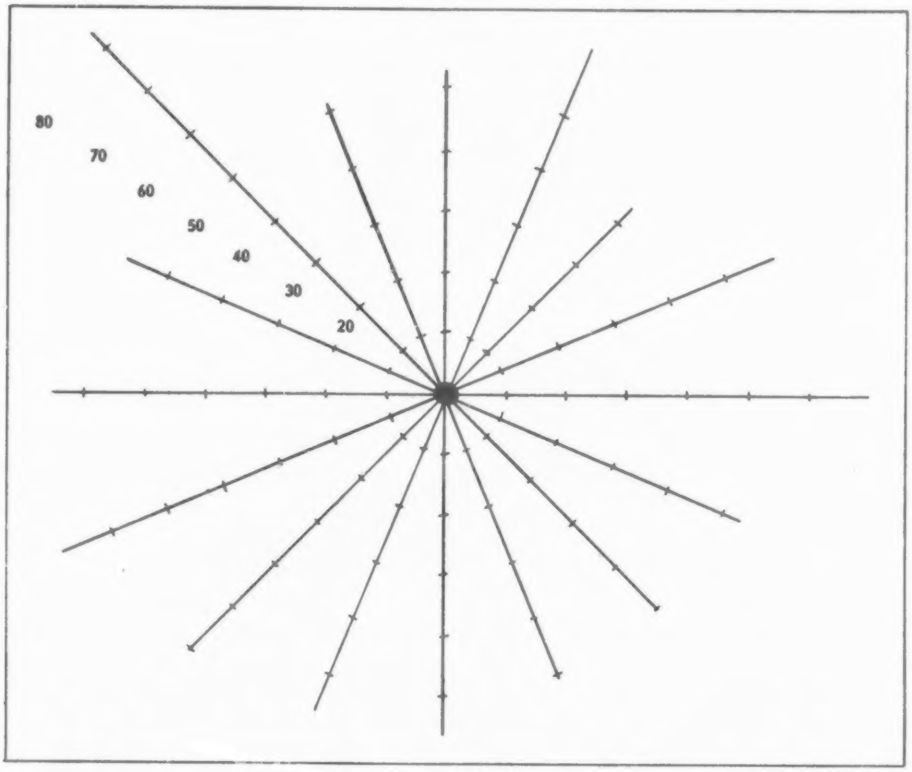

Figure 7. Wind rose of percent frequency for each wind direction for visibilities of 0-12 miles at Salt Lake Municipal Airport in December. Data are the same as in Figure 3 except that only wind speeds of 1-10 mph are considered.

In December the mean maximum mixing depth is estimated to be 500 meters, just half of that in October. Furthermore, the lowest average wind speed of the year, 7.4 mph,[11] occurs in December. With such a low dispersive capacity atmospheric pollutants may be transported throughout the Salt Lake Valley and remain in a relatively concentrated state throughout the day. Therefore, pollution from various sources throughout the valley, where there are no control ordinances, is effective in reducing the daytime visibility at Salt Lake Airport in December. At the airport the effect of the control measures is expected to be most apparent in the forenoon, whereas the effect of uncontrolled emissions is expected to be most apparent in the afternoon. Consequently, the visibility improvement effected by control measures within Salt Lake City is overwhelmed by the uncontrolled emissions from developing areas throughout the valley. And in December there is a trend of declining visibility in the daytime.

Visibility data can be an important source of information in the evaluation of air pollution problems. In some cases the conclusions reached are straightforward, in more complex situations, however, additional information and more detailed analyses are required.

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DISCUSSION

PROFESSOR J. O. LEDBETTER: How were the regression lines fitted?

MR. HOLZWORTH: By the method of least squares. If you have reason to suspect that there is some other trend involved, you can compute other lines more detailed. We have done this in a few cases but it doesn't lead to any improvement.

MR. LICHTBLAU: Did you draw the conclusions on the deterioration of visibility at Lake Charles, as indicated from your diagram? Lake Charles was outstanding.

MR. HOLZWORTH: Yes, the frequencies of poor visibilities have increased in recent years at Lake Charles. It was brought to my attention only recently, in a compilation made here at the Taft Center. It is interesting to consider which of the cities that were listed have any type of control, and most of them do. Those that don't have any control are Caribou, Maine; Lake Charles, Louisiana; Pocatello, Idaho; and until very recently Oakland, California. So Lake Charles is one of the cities where there are no controls. What conclusions you draw from this, I am not sure. It would probably depend on having more data.

DR. SCHMIDT: It may be of interest to you that we studied the visibility from our light vessels that are situated 10 to 20 or perhaps 30 miles out from the coast. Comparing visibility before and after the war, we found a deteoriation of the visibility.

DR. HILST: What is the implication of before and after the war, increased industrialization after the war?

DR. SCHMIDT: Yes, sir.

MR. WOHLERS: I have a question. I am not a meteorologist. You have given quite a bit of data ranging from 1930 up to 1950 some odd, at various stations. How many men may have been on duty at those stations?

MR. HOLZWORTH: This is one of the matters that I hoped to bring out in listing the difficulties of using visibility data -- some of the factors that go into this year-to-year variation that you see. The only way I think that the data can be used is to assume that such variations are random. Obviously a great number of different people have taken part in those observations.

Smoke Concentrations in Montreal Related to Local Meteorological Factors

PETER W. SUMMERS, *Weather Engineering Corporation of Canada Ltd. and McGill University, Montreal*

Summary

Smoke concentrations in central Montreal have been measured by Weather Engineering Corporation since January 1960. The seasonal variations are related to the changes in atmospheric stability. Early in 1961 measurements were started by McGill University on the campus and on top of Mount Royal. Data from the three locations are compared and discussed in terms of the vertical distribution of smoke and local topographical effects. The advantage of a "smokeless zone" is clearly demonstrated. Some synoptic situations producing high smoke concentrations are illustrated. Application of these results to similar locations in eastern Canada and the northern United States with a long winter snow cover is discussed.

The first analysis of air pollution in Montreal in relation to local meteorological variables was presented one year ago at the Kingston meeting of the Royal Meteorological Society, Canadian Branch. Although based on a 4-month sample of smoke concentration measurements from only one location, in the downtown area, this study presented several interesting results and some tentative conclusions.

Since that time, measurements have continued and the seasonal and diurnal variations can now be analyzed in more detail. Measurements were started at the MacDonald Physics Building on the McGill University Campus at the end of January 1961 and on top of Mount Royal at the Canadian Broadcasting Corporation transmitter building in the middle of March 1961. The measurements from these two sampling locations can now be compared to determine the effects of the Mount Royal "smokeless zone". Also the measurements made at the top of Mount Royal at a height of 600 feet above the city can be used to evaluate the effect of inversions on the vertical transport of pollution. Some preliminary results of these studies will be presented.

SAMPLING EQUIPMENT

The equipment used for these studies is the Model E automatic spot sampler developed for the American Iron and Steel Institute by Hemeon[2] and manufactured by the Research Appliance Company of Pittsburgh.

In sampling with this equipment, a known volume of outside air is drawn through a given area of filter paper and the amount of dust and smoke particles deposited in a given time is evaluated by measuring the optical density of the soiled spot with a photometer. The method is described in full detail elsewhere.[2]

UNITS

The optical density is calculated as follows:

$$\text{Optical density (O. D.)} = \log_{10} \frac{I_o}{I}$$

where:

I_o = the intensity of transmitted light through the clean paper

I = the intensity of transmitted light through the soiled paper

For comparison with other samples the optical density is converted to a unit scale called the COH unit, defined as follows:

$$1 \text{ COH unit} = 100 \times \text{O. D.}$$

This value is still dependent on the volume of air drawn through the filter paper. If L is the quantity of air sampled expressed in thousands of linear feet then:

$$L = \frac{\text{flow (cu. ft. per min.)} \times \text{sampling time (min.)}}{1000 \times \text{area of spot (sq. ft.)}}$$

The standard unit used to express smoke concentration is:

$$\text{COH units per 1000 linear feet} = \frac{\text{O. D.} \times 100}{L}$$

INTERPRETATION OF COH UNITS

The New Jersey State Department of Health[3] carried out an extensive statewide survey of air pollution by means of smoke samplers in 1956. On the basis of informed opinion they assigned the following adjectival ratings to various levels of smoke concentration:

Smoke Concentration (COH units /1000 linear feet)	Adjectival Rating
0 - 0.9	light
1.0 - 1.9	moderate
2.0 - 2.9	heavy
3.0 - 3.9	very heavy
4.0 plus	extremely heavy

Many cities have recorded concentrations in the range of 8.0 to 12.0 COH units for sampling periods of 2 hours. In Montreal on April 14th, 1960, a maximum of 12.8 was registered between 1900 and 2100 EST. During one half-hour period from 1930 to 2000 EST a peak of 15.4 COH units was reached, under a very strong low-level warm frontal inversion.

During a period of forest fires in the fall of 1952 concentrations produced by a mixture of forest smoke and urban smoke reached 18.0 COH units in Pittsburgh. A reading of 23.0 units has been reported from Sydney, Australia, presumably from bush fires inland.

The adjectival ratings have been used by several other agencies and are used throughout this paper.

SAMPLING TIME

The relation between the quantity of smoke in the atmosphere and the otpical density was found to be linear for values of I less than 50 percent. With the flow rate and spot size used in our samplers this value often was exceeded for 2-hour samples in the winter months. Therefore, a standard 1-hour sampling period was used at all three locations from October to May. One-hour samples have the added advantage of convenient correlation with meteorological variables such as wind and temperature, which are normally tabulated on an hourly basis in published summaries.

During most of the first year the Weather Engineering sampler was operated on a 2-hour sampling period and was changed to a 1-hour period only when necessary. Thus some of the data represent averages over a 2-hour sampling period.

LOCATION OF SAMPLERS

The location of the three smoke samplers with respect to Mount Royal and the downtown Montreal area is shown in Figure 1, which also indicates the height of the air intake above sea-level. The McGill and Weather Engineering intakes are situated about 35 feet above the ground; the CBC intake is 12 feet above ground.

The following abbreviations are used throughout:

WEC	--	Weather Engineering Corporation sampler located on Crescent Street
McGill	--	McGill University sampler located on the Campus
CBC	--	McGill University sampler located in the

Canadian Broadcasting Corporation building
on top of Mount Royal

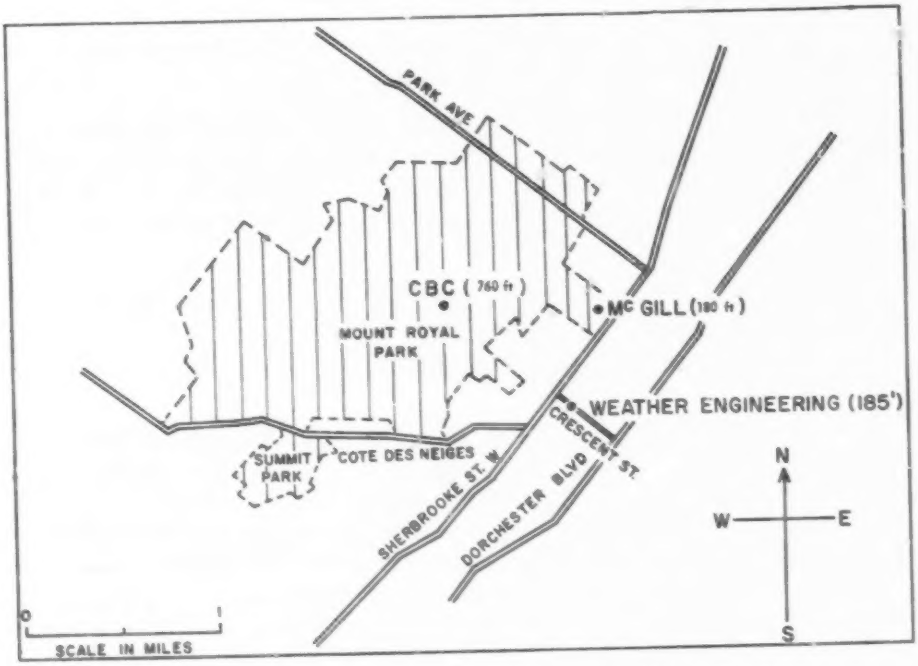
PARK AVE
CBC (760 ft)
MOUNT ROYAL PARK
Mc GILL (180 ft)
WEATHER ENGINEERING (185')
CRESCENT ST.
SUMMIT PARK
COTE DES NEIGES
SHERBROOKE ST. W.
DORCHESTER BLVD
N
W
E
S
0
1
SCALE IN MILES

Figure 1. Location of samplers with respect of Mount Royal

SEASONAL VARIATION IN SMOKE CONCENTRATION

Figure 2 shows a plot of the monthly averages at WEC from January 1960* to September 1961. This figure indicates a very marked seasonal variation. Readings remained in the top half of the heavy range from January to April 1960 and then fell sharply during May to relatively low readings from June to August. Only in July, however, did the monthly average fall into the light range. Beginning in August the concentrations increased steadily, reaching the heavy range again by November. During January 1961 concentrations reached a peak in the very heavy range. From January on they declined steadily until May. During the summer of 1961 values remained almost constant near 1.0 COH unit. September 1961 was the warmest on record in Montreal, with a mean temperature nearer to that expected in July or August; the smoke concentration during this month was lower by 27 percent than the corresponding value for September 1960.

There are two reasons for the marked seasonal trend:

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*Note the January 1960 average is based on 16 days only.

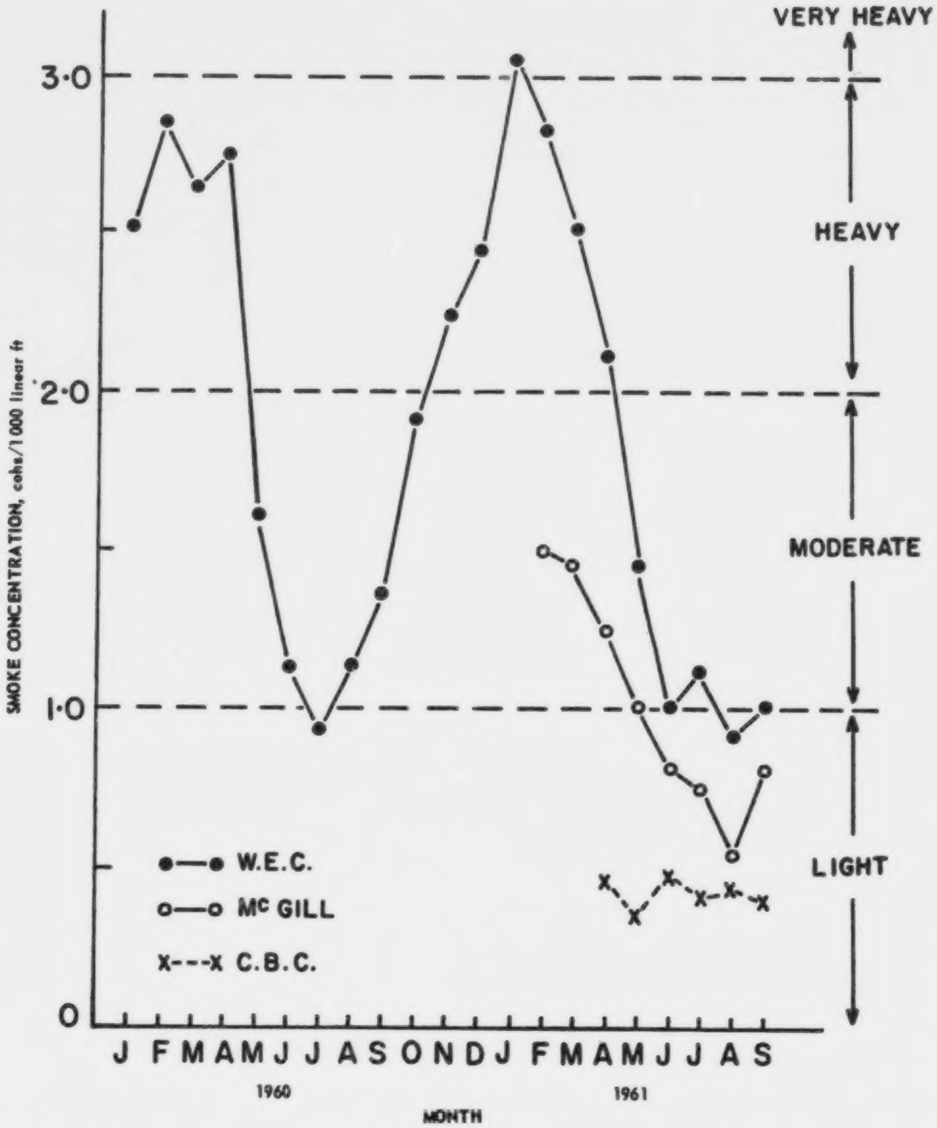


Figure 2. Average monthly smoke concentrations in Central Montreal, January 1960 to September 1961

1. The emission of smoke into the atmosphere is much higher during the long winter heating season.
2. The ventilation of the city's air is severely restricted in the winter months because of the almost continuous stability of the atmosphere and frequent temperature inversions caused by snow-covered or frozen ground.

These two factors combine to give smoke concentrations in midwinter nearly three times those of midsummer.

The effect of snow cover on smoke concentrations in the spring is shown in Figure 3. This diagram shows a plot of the 21-day running means from February to mid-May for 1960 and 1961. The readings are very close until about March 17th, when the 1961 readings began to fall below the corresponding 1960 values; by April 10th they were 0.8 COH units lower. During April 1961 the smoke concentrations averaged 24% lower than in 1960.

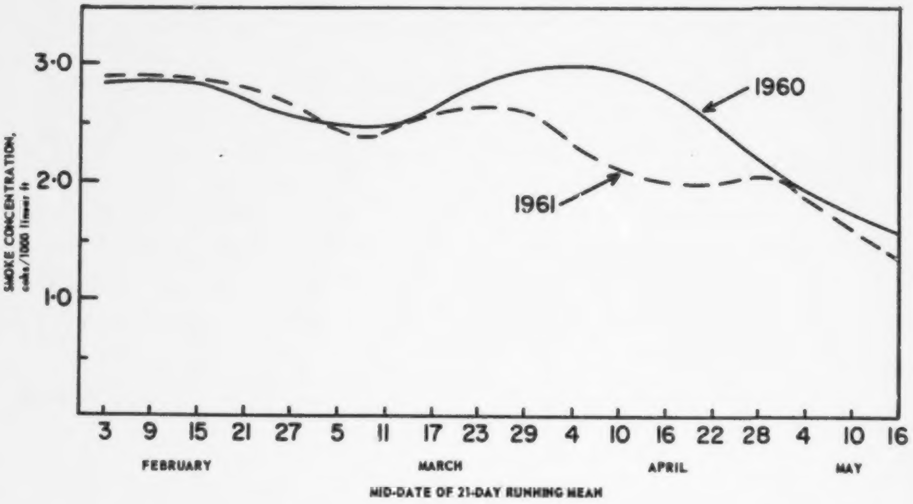


Figure 3. Twenty-one-day running mean at WEC late winter and spring 1960, 1961

There are two possible reasons for this: either less pollution was emitted into the atmosphere during April 1961 or the dispersion of the pollution by the atmosphere was much greater.

Since the mean temperature was 1.0°F lower in 1961 the first reason can be discounted. Heating plants should have produced about the same amount of smoke, and there is no evidence of any reduction in emissions from other sources such as transportation and industry.

One must look, then, for a meteorological reason to explain the increase in ventilation. The percentage variation in mean wind speed and precipitation between the two Aprils was less than that for some of the other months, February, March and May; therefore winds or precipitation cannot be the cause. Synoptically the weather patterns were rather similar, with frequent storms in both Aprils. In the absence of any low-level temperature soundings, the frequency of temperature inversions cannot be determined accurately.

The only significant difference between the two winters was the snow cover. The total snowfall in Montreal in the 1959-1960 winter season was 120 inches; in the 1960-1961 season it was only 86 inches.

By March 8th, 1961, the snow cover at Dorval Airport was down to 2 inches and had disappeared from many parts of the city. Two heavy snowstorms in mid-March increased the depth again, but the last snow cover disappeared one week earlier than in 1960. Throughout April there were frequent rains, which speeded the thawing-out of the ground so that the chilling effect of the ground on the air ended much earlier in 1961 than in 1960. Thus the lowest layers of the atmosphere became unstable earlier in 1961 and allowed increased ventilation, which caused the lower smoke concentrations in April 1961.

The readings at McGill show exactly the same seasonal trend, but the magnitude of the readings is lower by a factor of one-third to one-half. This difference between the two locations will be discussed later.

The few months of data available from the CBC location show little evidence of any marked seasonal variation. The average smoke concentrations from April through September have remained almost steady, whereas at WEC and McGill the values have halved. This suggests that although much less smoke is produced in the summer months, the increased vertical mixing due to convection carries the smoke aloft more readily.

In an earlier report[1] it was shown that during the period January 15th to April 30th, 1960, the highest smoke concentrations all occurred under inversion conditions caused either by the advection of warmer air from the south over the snow-covered ground or by low-level warm frontal surfaces over the city.

The stalling of warm fronts just south of the St. Lawrence and Ottawa valleys in the winter months is a feature well-known to meteorologists in the area. At times this stagnation can lead to prolonged spells of high smoke concentrations (well above 25 percent more than the 21-day running mean) as happened for 3-1/2 days in February 1960.

During the 1960-61 winter season high readings again occurred in these circumstances, but there was also a much greater frequency of anticyclonic weather, which produced equally high smoke concentrations. It therefore appears that two frequently occurring types of weather situations can lead to extremely high pollution levels in Montreal during the winter months. In most other large cities only one situation, the anticyclone, regularly causes high pollution levels. These meteorological influences will be illustrated by examples.

DIURNAL VARIATION OF SMOKE CONCENTRATION

Seasonal Change in Week-day Diurnal Variations at WEC.

A study of the week-day diurnal curves for the months January 1960 to September 1961 indicates the same basic daily variation in every month. Each day has two maxima (shortly after sunrise and in the evening) and two minima (early morning and early afternoon).

The shape of the curves shows a continual transition from month to month. The curves can be classified into two basic types, examples of which are illustrated in Figure 4. Type A

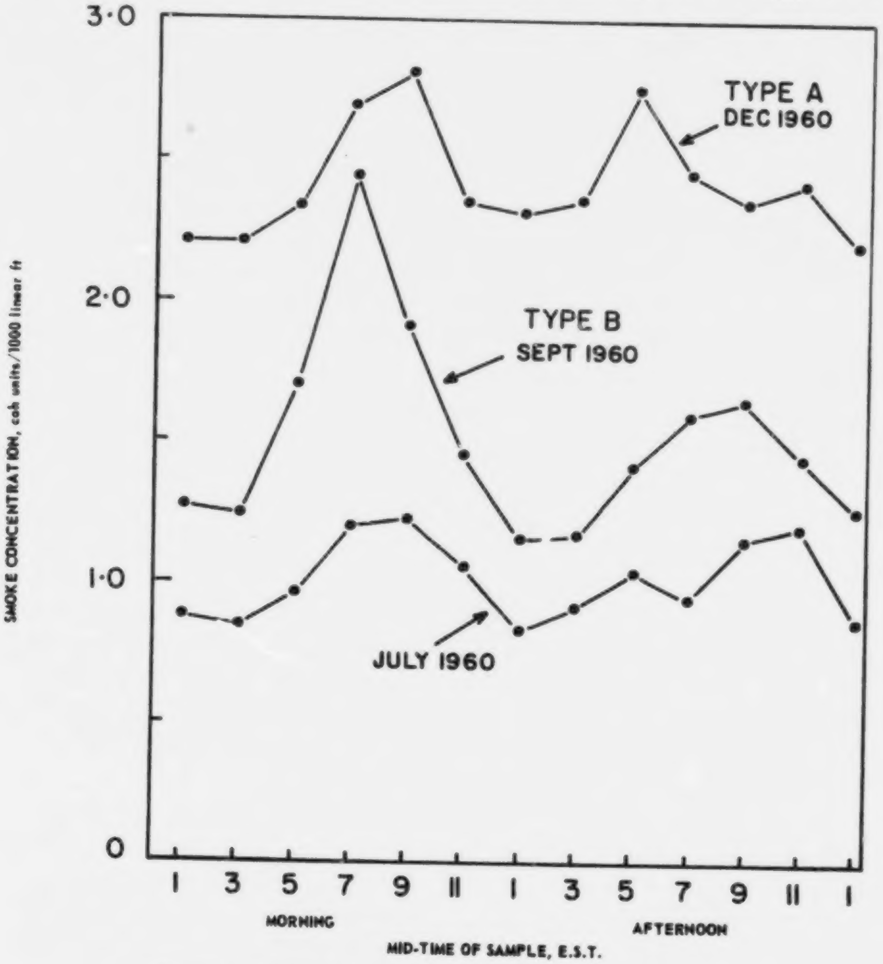


Figure 4. Examples of weekday diurnal curves at WEC

has a small diurnal amplitude of less than 35 percent. The maximum occurs in the morning; the early evening peak is near and at times higher than the morning peak. Type A occurs from November through April. Type B has a large diurnal amplitude of more than 50 percent with a strong peak in the morning. It occurs from May through October.

In Figure 5 the top curve shows the diurnal amplitude expressed as a percentage of the monthly average and indicates a pronounced seasonal variation. In the winter months the atmosphere remains stable for most of the day and overnight; hence the diurnal variation is relatively small. In the late spring and particularly in the late summer and fall, great stability develops

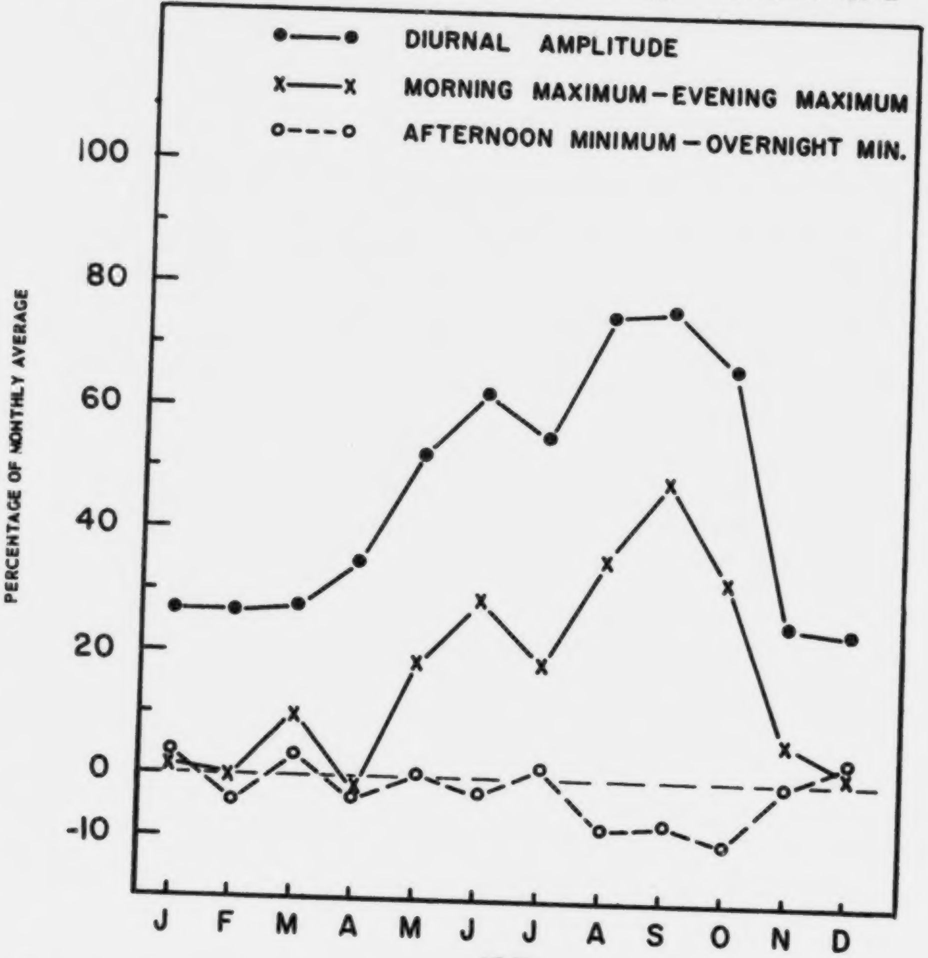


Figure 5. Diurnal amplitude, morning maximum minus evening maximum, afternoon minimum minus overnight minimum as a percentage of average weekday values

overnight and is followed by daytime instability leading to large diurnal variations. In mid-summer (July) the atmosphere tends to remain unstable at times through the night hours or at least develops no great stability. This leads to somewhat smaller diurnal variations as indicated in Figures 4 and 5.

The middle curve on Figure 5 shows the difference between the morning maximum and the evening maximum again expressed as a percentage of the average monthly smoke concentration. This curve indicates that the morning maximum is most pronounced in the fall, whilst in the winter there is little difference between the two maxima.

The bottom curve on Figure 5 shows that the two minima are almost of equal magnitude, although in the fall the lowest readings tend to occur in the afternoon rather than overnight.

A full explanation of the shape of these diurnal curves cannot be given at this time. The actual smoke concentration at any given time is a function of both the rate of smoke production and the rate of ventilation during the preceding few hours. Both of these vary throughout the day and although the diurnal changes can be assessed subjectively, the absolute magnitudes cannot be obtained at present.

The morning peak shortly after sunrise is generally ascribed to a Hewson[4] fumigation and although this undoubtedly occurs on occasions in Montreal, the curves in Figure 4 show little indication of this on the average. Rather there is an almost steady increase in concentration from 0200 EST until shortly after sunrise. The gradual buildup probably occurs because during these hours more pollution is produced than can be ventilated. The rate of ventilation increases sharply after sunrise and more than offsets the big increase in production due to daytime traffic and industry until late afternoon. By late evening the rate of ventilation has fallen off again but is still greater than the rate of production after man's daytime activities have ceased. Pollution therefore falls to a minimum again shortly after midnight.

Comparison of Week-day with Week-end Diurnal Variations at WEC.

From November through March the day-to-day variations in pollution are so large that even with a sample of 30 observations at any given time for each day of the week no significant variations were found.

Average values of smoke concentration were found to be 10% lower on week-ends, but the individual diurnal curves were very erratic. Once a larger sample is obtained allowing the effects of random day-to-day meteorological changes to be supressed then a comparison can be made between rates of production of pollution on week-days and week-ends.

During the summer months June to August 1960 and 1961 the day-to-day variation in the meteorological variables was not so great. Although the sample consisted of only 26 observations for each day of the week, significant variations were found between week-ends and week-days. The daily average was higher for every week-day than for the week-end. On Saturdays the average smoke concentration was 20 percent less than on week-days; on Sundays it was 25 percent less. The curves are shown for comparison in Figure 6.

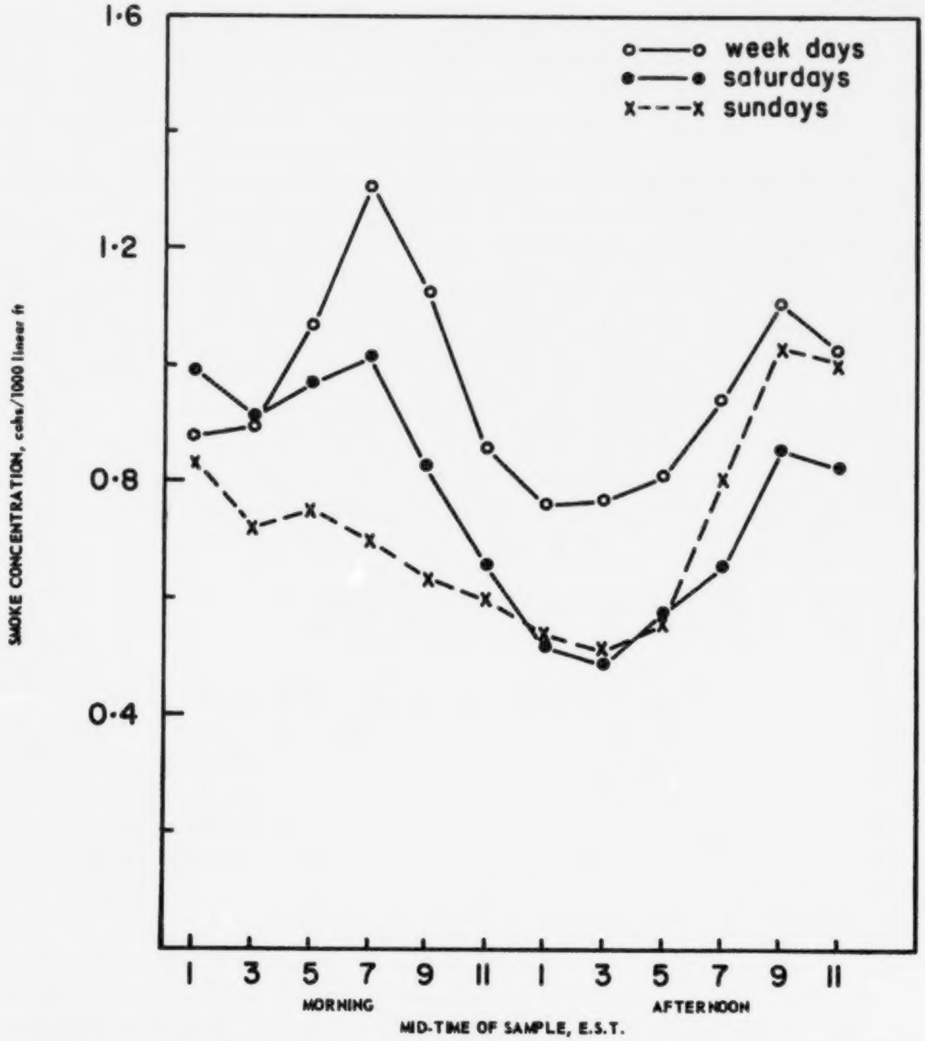


Figure 6. Comparison of weekday with weekend diurnal variations at WEC for the summer months June to August 1960, 1961

If we assume that the factors affecting ventilation are the same on week-days as on week-ends, then the differences between the curves in Figure 6 must be explained in terms of differing rates of production of pollution. We know that industrial activity is much less over the week-end and that the flow of traffic is very different.

Perhaps the most significant feature of Figure 6 is the complete breakdown of the normal diurnal variation on Sunday. There is no morning peak because most of man's activities are at a standstill in the early hours of Sunday.

Comparison of Diurnal Variations at Top and Bottom of Mount Royal

By April 1961 the sampler on top of Mount Royal was operating on a regular basis. The 1-hourly readings are compared with those at McGill for the month of April. This small sample, based on 20 days, could not be combined with observations for May since the change to Daylight Saving Time shifts the daily cycle of production one hour with respect to the daily cycle of ventilation.

Figure 7 is an example of the type of comparison that may be made when more data become available.

The McGill curve shows evidence of a Hewson fumigation immediately after sunrise between 0500 and 0600 EST.

The maximum at the top of Mount Royal at 0800 EST indicates a lag of 2 hours after the overnight stability has broken down sufficiently to allow maximum transfer of pollution up to that level.

EFFECT OF MOUNT ROYAL "SMOKELESS ZONE" ON SMOKE CONCENTRATIONS

Nine hundred and fifty-seven simultaneous hourly observations of smoke concentration for week-days only at WEC and McGill during February and March 1961 were tabulated according to the wind directions recorded at Dorval Airport. The mean concentrations for each of the eight cardinal compass points are shown in Table 1. The following conclusions can be made from this table:

1. Averaged over the quadrant north through east to south, where the Mount Royal smokeless zone can have no effect, the smoke concentrations at McGill are 33 percent lower than at WEC. The reason is that the immediate surroundings of McGill have fewer sources of pollution.

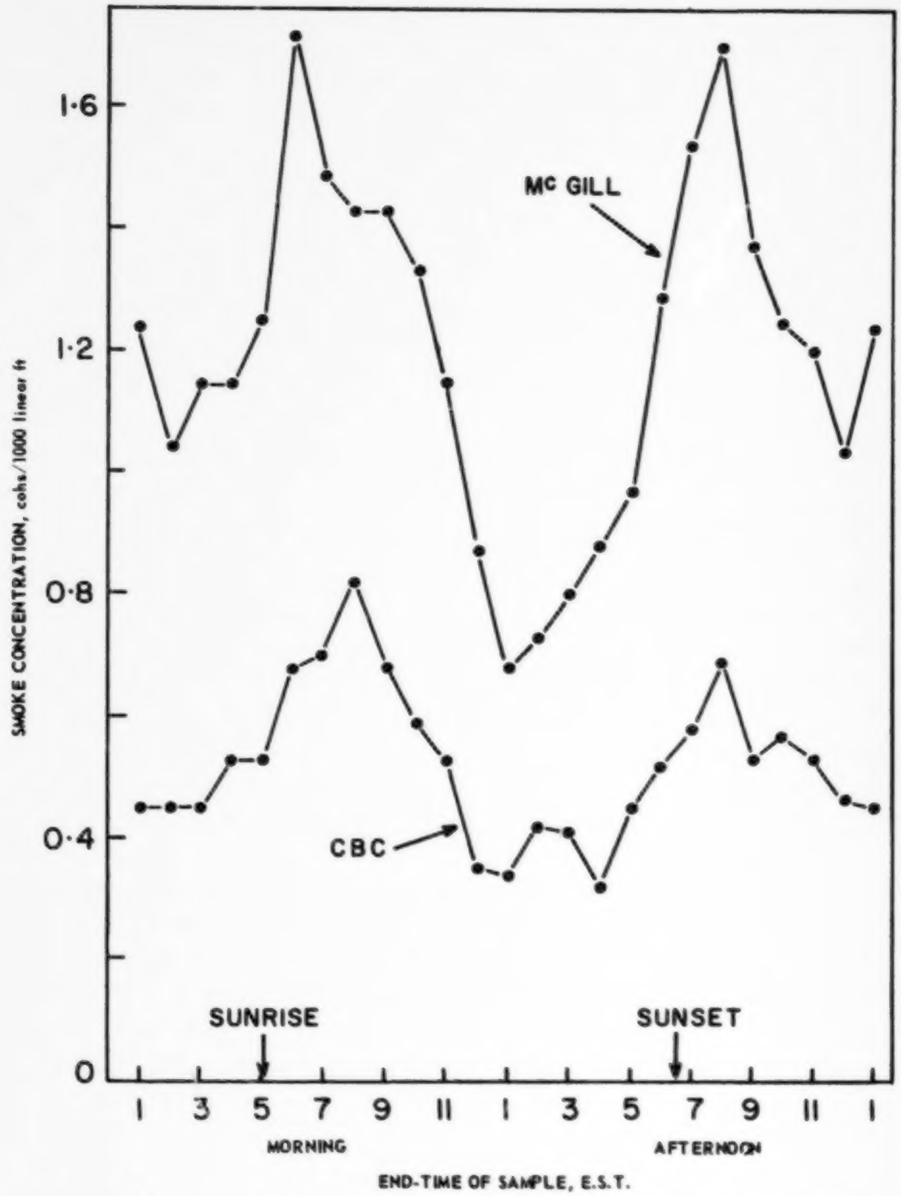


Figure 7. Comparison of diurnal variations at top and bottom of Mount Royal for April 1961

2. When winds are tabulated on a 16-point compass the greatest frequency is from the west-southwest rather than southwest (see Figure 8); the majority of the southwest winds shown in Table I are really west-southwest winds. With winds from this direction the air at the McGill Sampler has passed over Westmount Summit Park and skirted Mount Royal Park and has

picked up very little pollution during the last 2 miles of its trajectory. Thus the McGill readings drop to 0.8 COH units. With southwest winds the buffering effect of the smokeless zone is not felt at WEC, where the average concentration is 2.7 COH units.

TABLE I

EFFECT OF MOUNT ROYAL "CLEAN AREA" ON SMOKE CONCENTRATIONS AT WEC AND McGILL DURING FEBRUARY AND MARCH 1961

	N	NE	E	SE	S	SW	W	NW	Calm
Percentage Frequency	15	20	55	6	6	31	14	3	1/2
Mean Wind Speed, mph	9.8	14.2	10.3	11.2	7.7	13.4	15.4	9.8	--
Mean Smoke Concentration at WEC, COH units	3.4	2.9	3.3	2.9	3.9	2.7	1.6	1.8	4.1
Mean Smoke Concentration at McGill, COH units	2.2	1.9	2.4	2.0	2.6	0.8	0.6	1.4	3.5

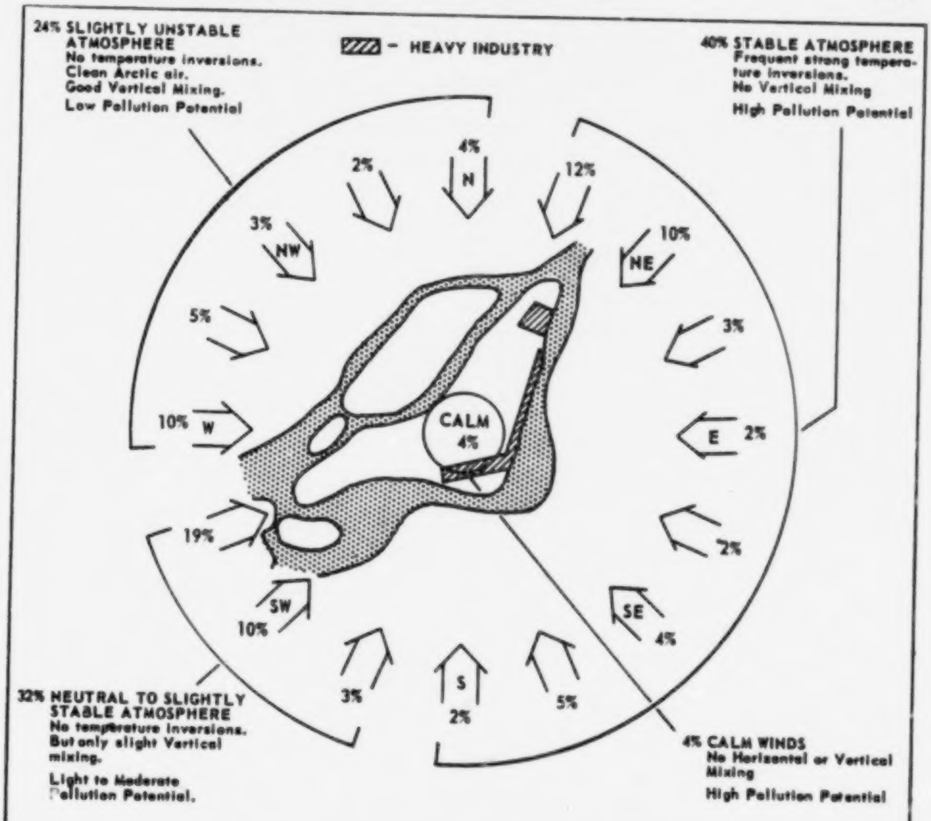
3. The McGill site has even better protection with winds from the west, and concentrations drop to 0.6 COH units. At WEC the west winds have passed over the edge of the Park, and concentrations drop to 1.6 COH units.

4. With northwest winds both McGill and WEC are protected by the Park, and smoke concentrations are similar.

5. In calm conditions the Park has no effect and readings at both locations are high.

Even without the Park, winds from southwest through north could be expected to give lower smoke concentrations because stability is lower and ventilation is therefore increased. (see Figure 8).

A similar analysis has been done for June to August 1961. This analysis shows the same general trend in variations of smoke concentration but with the following important differences:


24% SLIGHTLY UNSTABLE ATMOSPHERE
No temperature inversions.
Clean Arctic air.
Good Vertical Mixing.
Low Pollution Potential
▨ - HEAVY INDUSTRY
40% STABLE ATMOSPHERE
Frequent strong temperature inversions.
No Vertical Mixing
High Pollution Potential
4%
N
2%
12%
3%
NW
10%
NE
5%
3%
10%
W
CALM
4%
E
2%
19%
2%
SW
10%
SE
4%
3%
S
2%
5%
32% NEUTRAL TO SLIGHTLY STABLE ATMOSPHERE
No temperature inversions.
But only slight Vertical mixing.
Light to Moderate Pollution Potential.
4% CALM WINDS
No Horizontal or Vertical Mixing
High Pollution Potential

Note: These composite wind data are for the months November to April for the 10-year period 1947 to 1956 at Dorval Airport and were supplied by the Meteorological Branch, Department of Transport.

Figure 8. Location of heavy industry on Island of Montreal together with the wind frequencies for the months November to April

1. Averaged over the quadrant north through east to south the smoke concentrations at McGill are only 16 percent lower than those at WEC.
2. With southwest and west winds the reduction at McGill is only 45 percent, compared to a reduction of 60 to 70 percent in the winter.

These values indicate that although Mount Royal has an appreciable effect in the summer, it is not nearly so marked as in the winter. This is to be expected, since a much larger proportion of the total smoke in summer is due to the more distant industrial sources rather than to local household and commercial heating plants.

RELATION OF SMOKE CONCENTRATIONS TO SYNOPTIC FEATURES ON THE WEATHER MAP

Two cases will be discussed to illustrate how changes in the synotpic features of the weather map affect the smoke concentrations in Montreal.

Prolonged Spell of Anticyclonic Weather, March 20th to 24th, 1961

The surface weather maps during this period are shown in Figures 9 to 11. An Arctic cold front passed through Montreal late on March 19th, and the high-pressure area drifted slowly southeast from James Bay to a position just east of Montreal by the morning of the 22nd. The vertical temperature structure at Maniwaki, Quebec, (about 125 miles northwest of Montreal) during this period is shown in Figure 12. At 1200 G. M. T. (0700 EST) on the 20th the profile shows a shallow layer of cold air up to 940 mb. By the 21st subsidence associated with the high and advection of warmer air aloft, combined with strong nocturnal cooling at the ground, had created an extremely strong temperature inversion of 16°C in the lowest 600 feet of the atmosphere. This inversion persisted for three days, but by the 23rd its

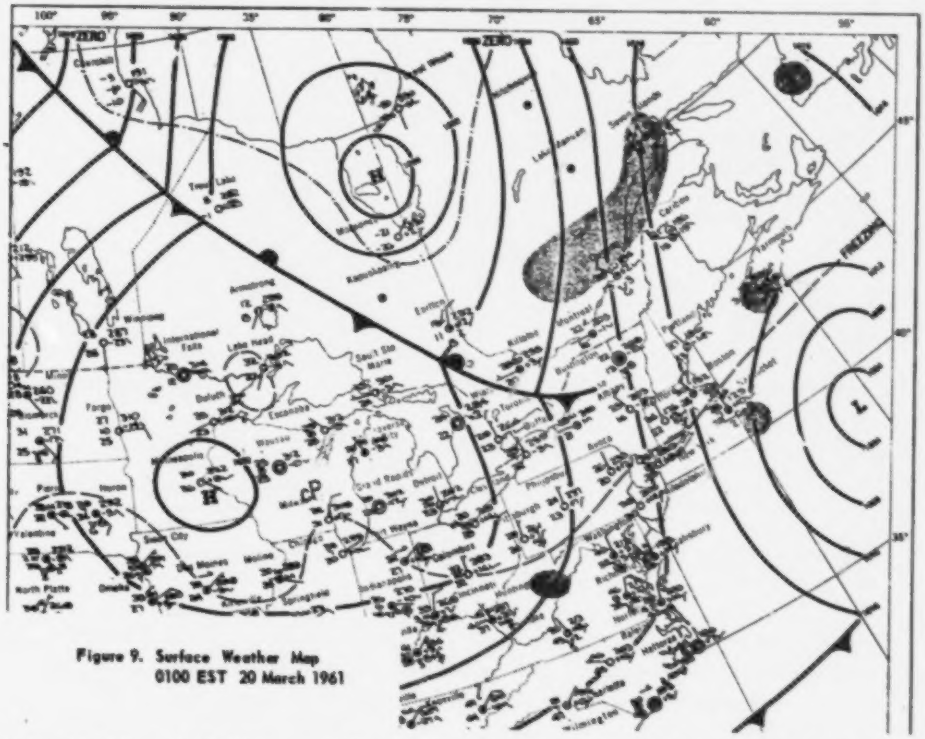
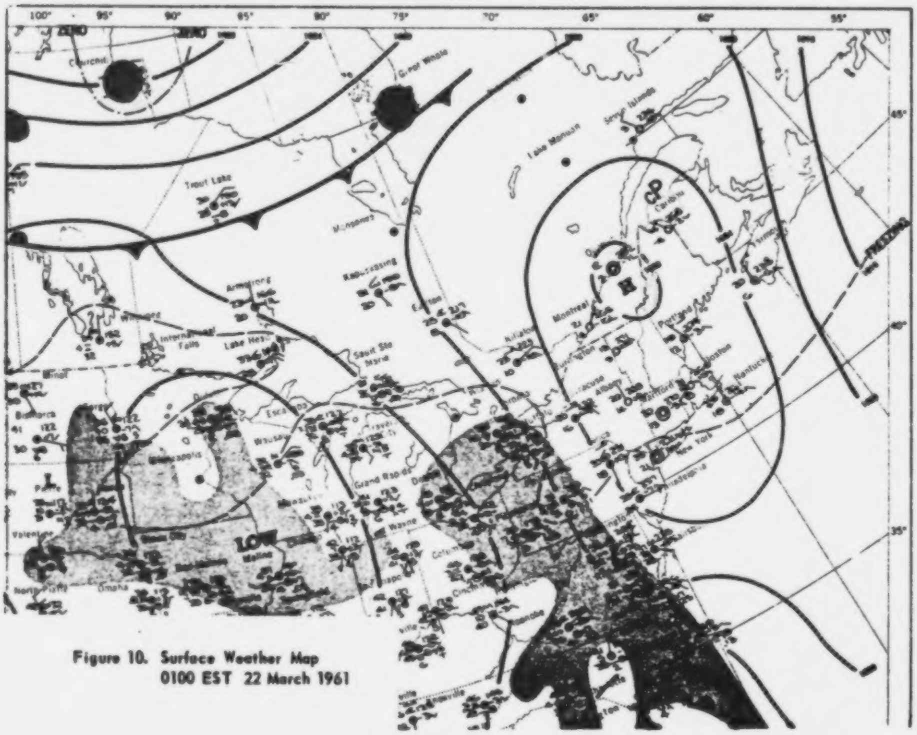


Figure 9. Surface Weather Map
0100 EST 20 March 1961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Seven Islands
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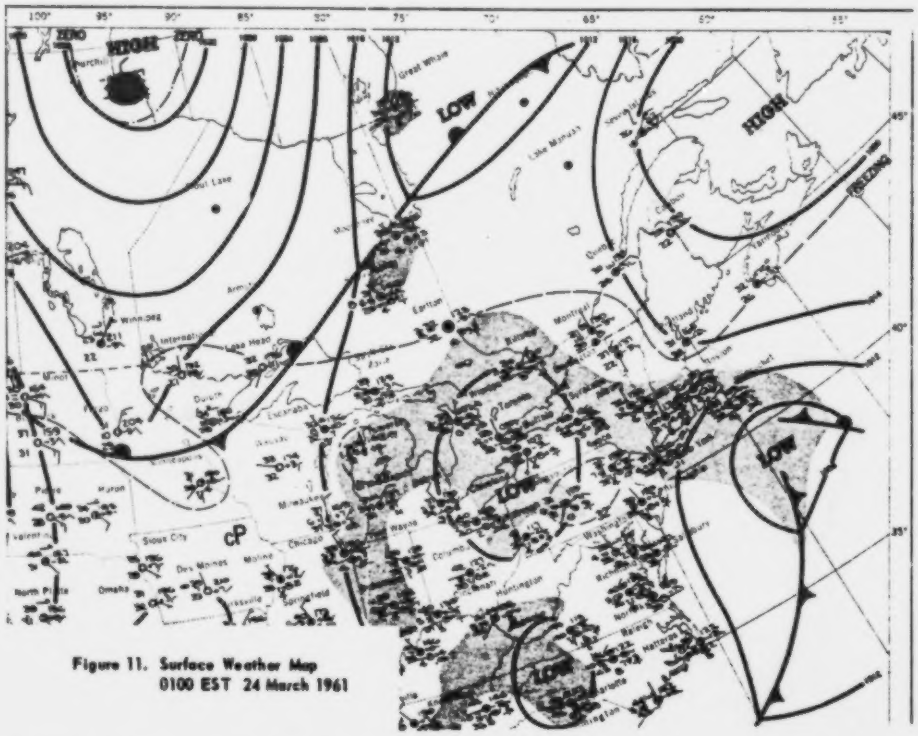
Montreal
Burlington
Portland
Albany
Boston
Hartford
Nantucket
New York
Philadelphia
Armstrong
Winnipeg
International Falls
Lake Head
Sault Ste Marie
Earlton
Minot
Minneapolis
Valentine
North Platte
Omaha
Sioux City
LOW
Moline
Grand Rapids
Detroit
Wayne
Columbus
Cincinnati
Wausau
Escanaba
FREEZING

Figure 10. Surface Weather Map
0100 EST 22 March 1961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LOW
Trout Lake
Lake Manouan
Seven Islands
HIGH
FREEZING
Winnipeg
International Falls
Lake Head
Earlton
Montreal
Quebec
Boston
LOW
Minot
Duluth
Escanaba
Minneapolis
Huron
Pierre
Valentine
Sioux City
cP
Des Moines
Moline
Chicago
Milwaukee
North Platte
Omaha
Springfield
Wayne
Columbus
LOW
Toronto
Huntington
Washington
Richmond
Salisbury
Raleigh
Hatteras
LOW
Charlotte
Wilmington

Figure 11. Surface Weather Map
0100 EST 24 March 1961

magnitude had decreased to 9° C in the lowest 400 feet.

On the 24th the high had moved off to the east as a small low drifted across New England from the west, and the anti-cyclonic inversion had completely disappeared. The cold front moved down rapidly from the northwest and passed through Montreal early on the 25th.

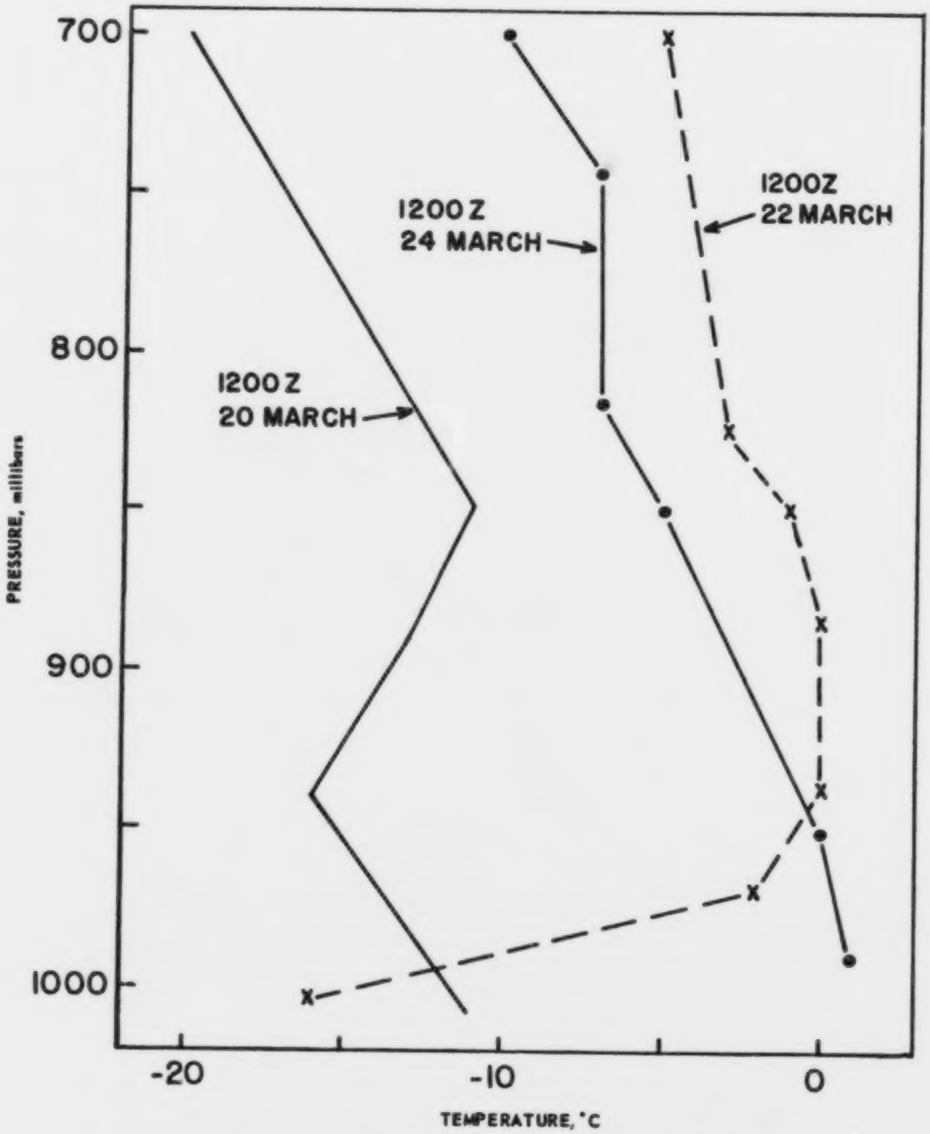


Figure 12. Vertical temperature profiles at Maniwaki -- March 20-24, 1961

The pollution record during this period for WEC and CBC is shown in Figure 13. The readings at McGill were in very close agreement with WEC and so are omitted from the diagram. Unfortunately, the CBC sampler was not operating at the beginning of the period. The morning peak occurred at WEC at varying times between 0400 and 1000 EST on each of the four mornings.

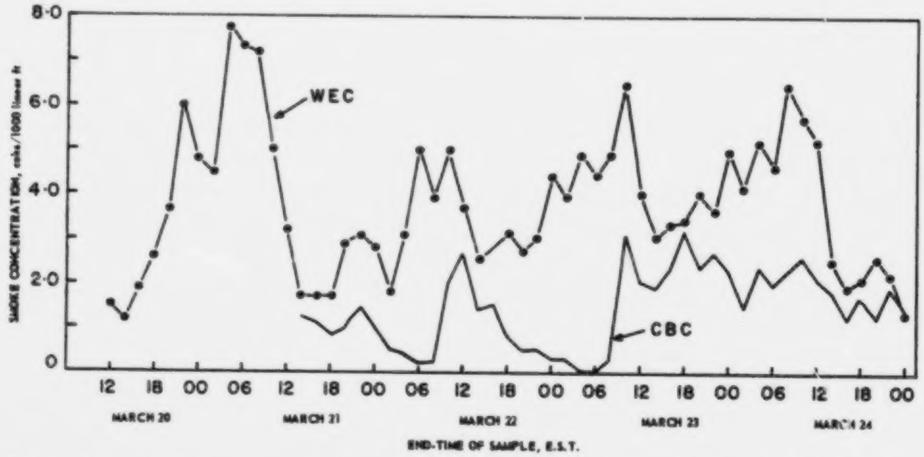


Figure 13. Smoke concentrations at WEC and CBC during prolonged spell of anticyclonic weather, March 20th - 24th, 1961

At CBC the concentration dropped to near zero at about 0600 EST on the 22nd and 23rd, an indication that the inversion was below the top of Mount Royal.

Between 1200 and 1300 EST on the 23rd the temperatures at Dorval Airport increased by 9° F indicating the final breakdown of the inversion. With only very light winds and a slightly stable atmosphere (see Figure 12), the concentration was again high at WEC on the morning of the 24th. At the top of Mount Royal, however, readings remained relatively high through the night of the 23rd/24th in the absence of the inversion. Smoke concentrations finally fell off on the night of 24th/25th because of freshening westerly winds and the passage of the cold front, which brought in clean Arctic air.

It is interesting to note the differences between the minimum temperatures recorded at the McGill Observatory and Dorval Airport during this period:

Date	Minimum Temperature, °F Dorval	 McGill	Temperature Difference, °F
March 21	2	11	9
22	10	14	4
23	10	26	16
24	31	34	3

There is no doubt that smog is one of the factors that contributes to large differences in temperatures between cities and the surrounding countryside on a night of strong nocturnal radiation cooling. In Figure 13 the average smoke concentration is lower during the night of the 21st/22nd than on the preceding and following nights and could account for the much lower temperature difference. Cloud cover on the night of 23rd/24th produced a general restriction in nocturnal cooling.

Variations in Smoke Concentrations during the Passage of a Storm

Figure 14 shows the variations at WEC and McGill during the period February 12th to 15th, 1961. At this time the sampler

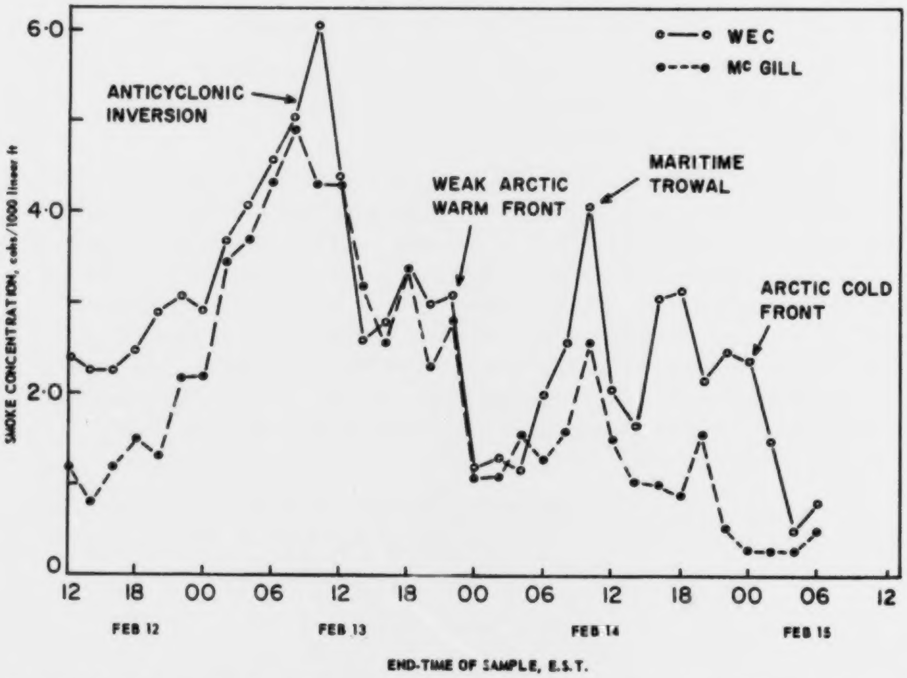
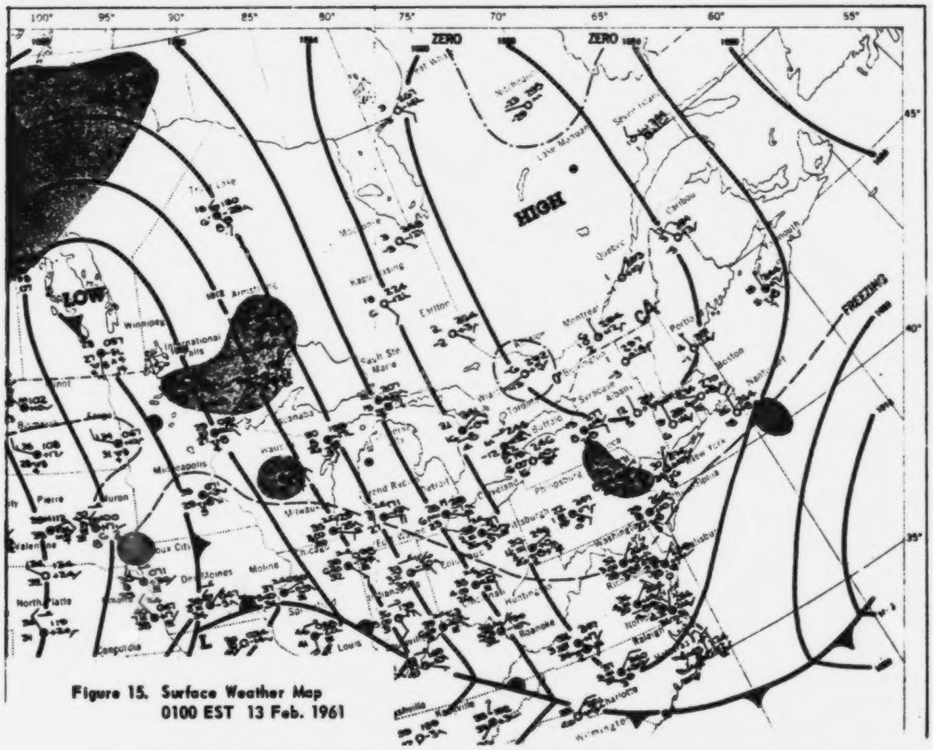


Figure 14. Variations of smoke concentration at WEC and McGill during passage of ridge of high pressure and storm, February 12th - 15th, 1961

had not been installed on Mount Royal. The surface weather maps are shown in Figures 15 through 17.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LOW
FREEZING
Montreal
Boston
Winnipeg
International Falls
Sault Ste Marie
Minneapolis
Pierre
Huron
Sioux City
Des Moines
Moline
North Platte
Detroit
Cleveland
Pittsburgh
Buffalo
Albany
Portland
Caribou
Quebec
Washington
New York
Raleigh
Charlotte
Wilmington
Knoxville

Figure 15. Surface Weather Map
0100 EST 13 Feb. 1961

Smoke concentrations were extremely high on the morning of the 13th under a strong anticyclonic inversion. On this occasion the minimum temperature at Dorval Airport was -6°F compared to 8°F at the McGill Observatory.

At noon on the 13th the winds at Dorval increased to 15 mph from the east or northeast, but smoke concentrations remained high under a warm frontal inversion. At 2100 EST a weak Arctic warm front (not shown on Figures 12 and 13) passed through Montreal. It was followed by a strong southerly gradient with southeast winds between 15 and 20 mph, which produced low smoke concentrations. With the approach of a trowal (shown as an occlusion on Figure 16) the surface winds decreased and the increased stability due to over-running warm air at low levels produced another sharp peak in pollution at 1000 EST. For the remainder of the day winds were steady from the southwest at 20 mph, but the concentrations at WEC did not decrease significantly until after the passage of the Arctic cold front at midnight, which brought westerly winds at 20 to 30 mph.

The lower concentrations at McGill during the afternoon and evening of the 14th are due to the effects of Mount Royal.

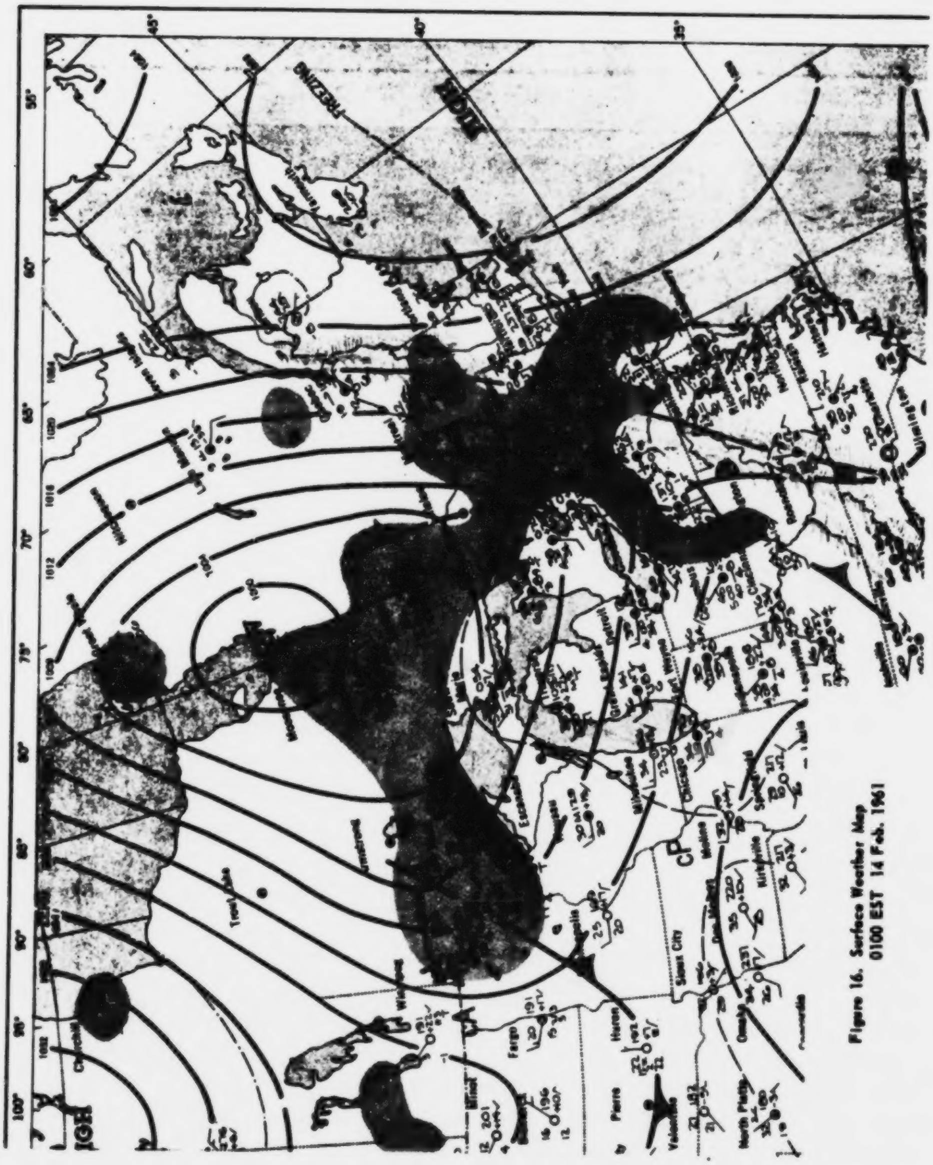
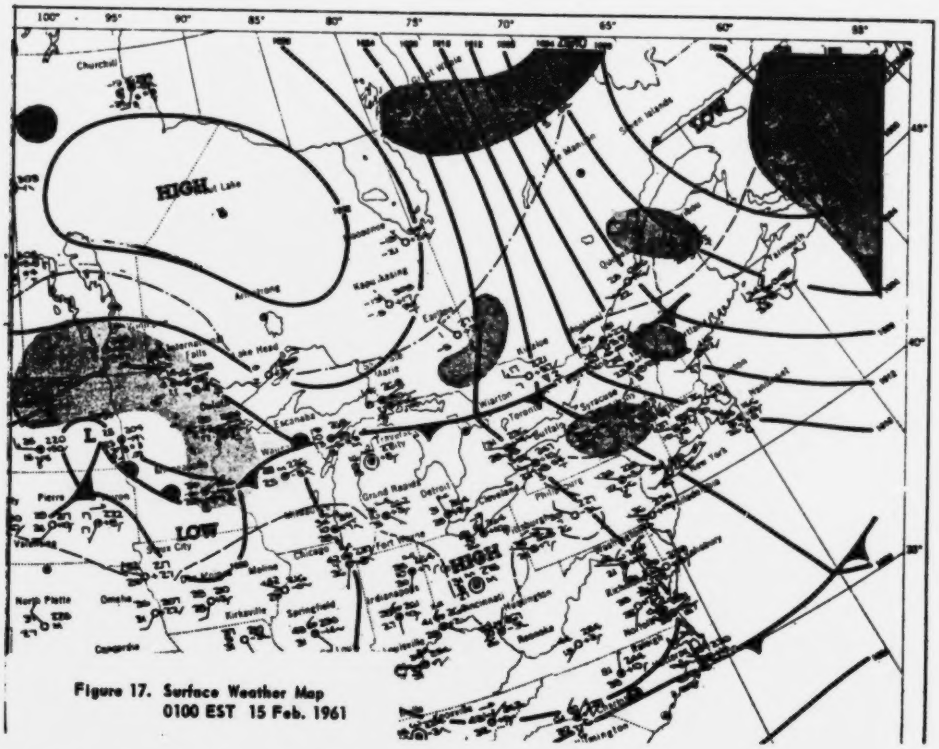

HIGH
FREEZING
Chicago
Milwaukee
Winnipeg
Fargo
Huron
Pierre
Sioux City
Omaha
North Platte
Moline
Washington

Figure 16. Surface Weather Map 0100 EST 14 Feb. 1961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LOW
Churchill
North Platte
Omaha
Chicago
Detroit
Cleveland
Toronto
Buffalo
Syracuse
New York
Philadelphia
Grand Rapids
Springfield

Figure 17. Surface Weather Map
0100 EST 15 Feb. 1961

Summary and Conclusions

The preceding analysis clearly shows that the seasonal and daily variations of smoke concentration in central Montreal are intimately related to changes in the meteorological variables. In particular the effect of winter snow cover is very important in that it produces almost continuous stability and frequent temperature inversions in the lowest levels of the atmosphere at a time of the year when the emission of pollution is at a maximum.

The problem is further aggravated by the relative location of the heavy industrial areas in Montreal. Pollution from these industrial sources is blown directly across some or all of the business and residential sections of the Island during the 40 percent of the time in the winter months, when the atmospheric conditions are least able to disperse it. This is illustrated diagramatically in Figure 8.*

The advantage of a "smokeless zone" such as Mount Royal Park is very evident in that pollution concentrations in the surrounding areas are reduced considerably.

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*Wind frequencies were compiled from data supplied by the Meteorological Branch, Department of Transport.

Although strong inversions form in Montreal under anticyclonic weather conditions, they occur just as frequently due to the advection of warm air at low levels in the atmosphere over the cold ground.

The second effect is most pronounced at a location which:

1. has a long and continuous period of snow cover;
2. lies in a valley orienated in a general east to west direction so that cold air is either trapped or funnelled in at ground level;
3. is near to or north of the main winter storm tracks to provide frequent periods of low-level warm air advectation just above the cold air.

Montreal, with a population of 2 million, is the largest urban area in North America to satisfy all the requirements for a pronounced inversion of the second type, a factor that hitherto has not been considered in air pollution studies. Since these conditions probably occur in other rapidly growing urban areas in central Canada and the northern United States, they should be taken into account for urban planning and the location of industrial plants.

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3. New Jersey State Department of Health, "State-wide Air Pollution Survey -- Smoke Index," 1958.
4. Hewson, E. Wendell, "Atmospheric Pollution," Compendium of Meteorology, pp. 1147, 1951.

DISCUSSION

DR. HEWSON: Do you have other examples of trapping below warm fronts, especially slowly moving warm-front systems? It seems to me that this is a situation in which one might expect quite high concentrations. You had one brief period of it during your study.

MR. SUMMERS: Yes, we did a study in the first winter, and we found that 20 percent of the time the air was being trapped under a warm front. This trapping effect is quite a well-known feature of the St. Lawrence and Ottawa valley region. It can persist for several hours, and on one occasion did persist for 2-1/2 days, a very high concentration.

DR. HILST: In your comparison of the McGill station and the effect of the Mount Royal Park, you pointed out that the McGill station was affected first, then it improved; the concentrations there went quite low, while yours stayed up. But then when you were both affected, their concentrations came up, rather than yours coming down. Do you have any explanation for this?

MR. SUMMERS: Not really, except that with the northwest wind the air is not blowing directly across the mountain but is going around the mountain, which would possibly affect it. This occurred in a very small percentage of the time, 4 percent. It was a very small sample.

DR. SCHMIDT: Mr. Summers, you talked about that morning maximum, and you talked a bit of the cause of that maximum. Did you also see something of a shift throughout the year?

MR. SUMMERS: Yes. The shift occurred within 2 hours after sunrise. And about 4 hours in the midwinter.

MR. MUNN: I have some comments about the evening peak that might be helpful. Recently I have been looking at data from a 200-foot tower in Ottawa, and also from a tower at Douglas Point in Ontario. We have found that in the early evenings, under light-wind, high-pressure situations, the inversion forms later on in the evening. The inversion doesn't collapse completely, but it diminishes somewhat, and comparable with this the wind at 200 feet is a maximum in the afternoon. It decreases in the early evening when the inversion reduces in intensity, and in the late evening the 200-foot wind increases. It is at that point that the pollution level goes up. I have found that the 200-foot wind increase is a very good predictor of an evening peak.

The Air Over Philadelphia

FRANCIS K. DAVIS, Jr., *Professor of Physics, Drexel Institute of Technology and Staff Meteorologist, WFIL-TV*

Summary

Simple air pollution theory indicates that relatively few meteorological and air quality observations are necessary in general air pollution studies. Even these relatively few observations are usually lacking, however, in studies of the behavior and quality of the air over a particular city. The observations of meteorological quantities related to air pollution should be standardized and the number of observations increased. Theory should be extended to include the complications brought about by characteristics of urban areas. At the same time, some useful rules for forecasting and regulating air pollution can be formulated for a city such as Philadelphia on the basis of currently available observational data.

THE PROBLEM

A steadily increasing population and a continuing trend toward industrialization within that population have resulted in an ever-increasing volume of the various waste products being poured into the atmosphere. Wanta and Stern (1957) point out that 21 percent of the world's people now live in cities with populations of 20,000 or greater and that by the middle of the next century the number will have increased to 90 percent. The population of the United States is increasing at a rate of 15 percent per decade, and the amount of energy expended per person is increasing yearly.

In spite of engineering efforts to reduce air pollutants to their least offensive form, they could become, if they are not already, a very serious health and economic problem in the Philadelphia area and in many other areas. Maneri and Megonnell (1960) describe the result of three statewide surveys of the extent and seriousness of air pollution in New York. Although these surveys were made independently by different agencies and with different techniques, a composite conclusion was reached: "Air pollution is a widespread complaint in New York State communities of all sizes, and its abatement and control receive too little attention."

When waste products have been discharged into the atmosphere, their subsequent life history is a meteorological problem. Even though pollutants are put into the atmosphere at a constant rate, the condition of the atmosphere will determine whether these contaminants accumulate to cause discomfort and damage

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or disperse enough that no problem results. Atmospheric conditions also determine whether such a problem will be localized in one small section of the community or will be widespread. Certainly any wise city planning activity should consider local weather conditions and their relation to air pollution when zones are set for industrial and residential development.

DIFFUSION PARAMETERS

When contaminants are released at a particular point, the atmosphere acts as its own cleansing agent by transporting and diffusing such contaminants, thus reducing their concentrations. A complete mathematical analysis of diffusion processes which would allow quantitative calculations is difficult. Diffusion equations are available from several sources, some of the most widely used being those developed by Sutton (1932, 1947). Such equations indicate that for a given contaminant emission the properties of the atmosphere of primary concern in determining concentrations at any point are wind speed, wind direction, and air stability as reflected by the temperature profile in the vertical direction. Very recent observations reported by Maneri and Megonnell (1960), Boettger (1961), Dickson (1961), Markee (1961), and Turner (1961) tend to confirm this indication. For example, Dickson reports a significant correlation of atmospheric pollution with all three properties; Markee reports high correlations between certain pollution levels and vertical temperature differences in Louisville; and Turner reports that the meteorological variables of wind speed, temperature, and stability account for about half of the variance in daily city-wide sulfur dioxide concentrations and soiling indices in Nashville, Tennessee.

DATA REQUIREMENTS

Relating meteorological parameters to air pollution concentrations in a given city is not a simple job. Although most large cities across the nation make air pollution measurements of some kind, there are no fixed standards for the type of measuring instruments to be used, for the general location and height at which such measuring instruments are exposed, or for the atmospheric conditions under which such measurements should be made. As a result, collection and comparison of pollution data in an effort to consider relative pollution levels in various cities across the nation, and even within a single city, are almost meaningless. It is highly desirable to accumulate data that would lead to standardization of pollution-measuring instruments and techniques so that a picture of pollution distribution on a nationwide basis and within a city can be established. Furthermore, Hemeon (1958) points out that we have yet to determine which of the many air pollution effects are objectionable, and that from an engineering viewpoint we have no objective basis for evaluating these air pollution nuisances.

In the meteorological department, measurements of wind speed and direction are available at many U.S. Weather Bureau Stations. These measurements, however, are frequently made at relatively high levels, often at airports located at some distance from urban areas and in topographical surroundings quite different from the urban area they represent. Low-level wind flow patterns throughout urban areas ought to be much more definitely understood under conditions of high pollution potential.

The vertical temperature structure of the air over a city is probably as important as the wind data in analysis of pollution problems. But in most cities no vertical temperature measurements are available. The vertical temperature distribution must be inferred from other measurements. For example, Turner (1961), in his Nashville study, proceeded on the premise that stability depends mainly on net radiation and wind speed and that net radiation is determined by the elevation of the sun and by the amount and height of cloud cover. He used these parameters to set up a stability classification.

Observations of the vertical temperature profiles have been made recently over Louisville, Kentucky. DeMarrais (1961) reports that these data show that stability conditions over an urban complex are quite different from those over open areas, where most other observations have been made.

Thus, it would also be highly desirable to standardize and increase the meteorological observations related to air pollution and to extend the observations and the theory to cover the complications brought about by the physical characteristics of urban areas.

METEOROLOGY OF THE PHILADELPHIA AREA

Although there is great need for additional meteorological and air pollution measurements to define more clearly the relationships between the two, existing observations and knowledge can often be combined and used to gain a greater measure of understanding of the air pollution problem in a particular city. In Philadelphia we recently undertook an investigation of the weather influences on urban air pollution with the aim of determining whether periods of potentially high air contamination might be anticipated on the basis of changing weather patterns.

To establish some of the detailed weather patterns for Philadelphia, a collection of hourly surface weather observations taken at the Philadelphia Weather Bureau Station at International Airport was analyzed. Through the cooperation of the National Weather Records Center in Asheville, North Carolina, these records were acquired in the form of WBAN-1 punch cards suitable for machine computations. They cover the period July 1949 through June 1959.

Studies such as those by Kleinsasser and Wanta (1956), Machta, Scott, and Korshover (1958), Keagy and Schueneman (1958), Neiburger (1959), and Niemeyer (1960) indicate that light winds are very highly correlated with high degrees of atmospheric pollution. Analysis of the Philadelphia data shows that the period of lightest winds is summer and fall, particularly late summer and early fall. This coincides with the period of maximum frequency of clear skies at night, which contribute to low-level cooling at night and to high stability. The large-scale weather observations indicate that poorest diffusion conditions in the Philadelphia area occur in the late summer and early fall and generally are associated with winds from the southwest. The late summer and fall are potentially the seasons of greatest air pollution risk in Philadelphia on the basis of low wind speeds, or low ventilation rate, alone. A detailed analysis of the general meteorological patterns for Philadelphia is presented in a report published by the Air Pollution Control Section, Department of Public Health, City of Philadelphia [Davis (1960)].

RELATION OF HIGH POLLUTION LEVELS TO METEOROLOGICAL CONDITIONS

In an effort to relate air pollution conditions in Philadelphia to weather conditions and weather patterns, dates of high particulate concentration in Philadelphia were obtained for the years 1957 through 1959. The particulate concentrations were recorded at two sites by high-volume and AISI samplers. The basis for classifying a daily reading as high was arbitrarily set at 1.5 times the monthly average. Since the list of dates selected on this basis was quite long, an additional criterion was imposed: the high-pollution dates must cover a period of 2 to 5 days in which readings for at least one of the days were high at both sampling sites and on both sensing devices.

This list totals 24 "episodes" covering 68 days, a little over 6 percent of the days in the 3-year period. The original list, however, included 125 days, or more than 11 percent of the total days. Seasonally, the distribution shows eight "episodes" in the winter months, four in the spring, two in the summer, and eight in the fall.

The general weather patterns associated with each of these pollution periods were investigated. Although these patterns were varied, some characteristics were persistent. On the basis of these a forecasting system could be set up to provide a warning when weather conditions likely to aggravate air pollution problems are developing. These conditions have a typical general history: a continental polar high-pressure center moves out of Canada across the Great Lakes, sometimes going slowly across New York State and off the Northeast coast, sometimes down into the Ohio Valley and eastward across the Middle Atlantic area to the Mid-east or Northeast coast. These highs become stationary or very slow-moving at the coast, and the Philadelphia area is influenced by very light winds for several days. During most of that period the high-pressure center is generally to the east, so the air flow is predominantly from a direction between southeast and southwest, with southwest heavily predominant.

Wind speeds during the problem periods were predominantly less than 8 mph; during 15 of those periods such speeds were recorded continuously for 14 hours or longer. High pollution levels were recorded with somewhat higher wind speeds in the spring season.

To associate wind directions with high pollution "episodes" more specifically, the hourly wind directions were tabulated for these periods. Figure 1 shows a composite wind rose for these high pollution periods. The high percentage of winds from west-southwest through south is apparent.

Because of the higher wind speeds associated with the spring episodes (March, April, and May), the high pollution periods for those months were analyzed separately. The over-all pattern for wind direction is not greatly changed, but the predominance of southwesterly winds is even stronger. Figure 2 shows the wind rose associated with high pollution episodes in the spring.

RELATION OF LOW POLLUTION LEVELS TO METEOROLOGICAL CONDITIONS

The weather conditions related to low levels of air pollution in Philadelphia were studied for the same 3-year period. Low levels were determined by records from the same samplers and were arbitrarily set at 0.6 of the monthly average or lower. The list included only those dates for which low readings were recorded at both locations. This list was heavily weighted with dates that fell on Saturdays and Sundays; these dates were eliminated because studies by the Air Pollution Control Section have demonstrated that the dramatic lowering of air pollution levels on weekends results from reduced community activity rather than from meteorological factors.

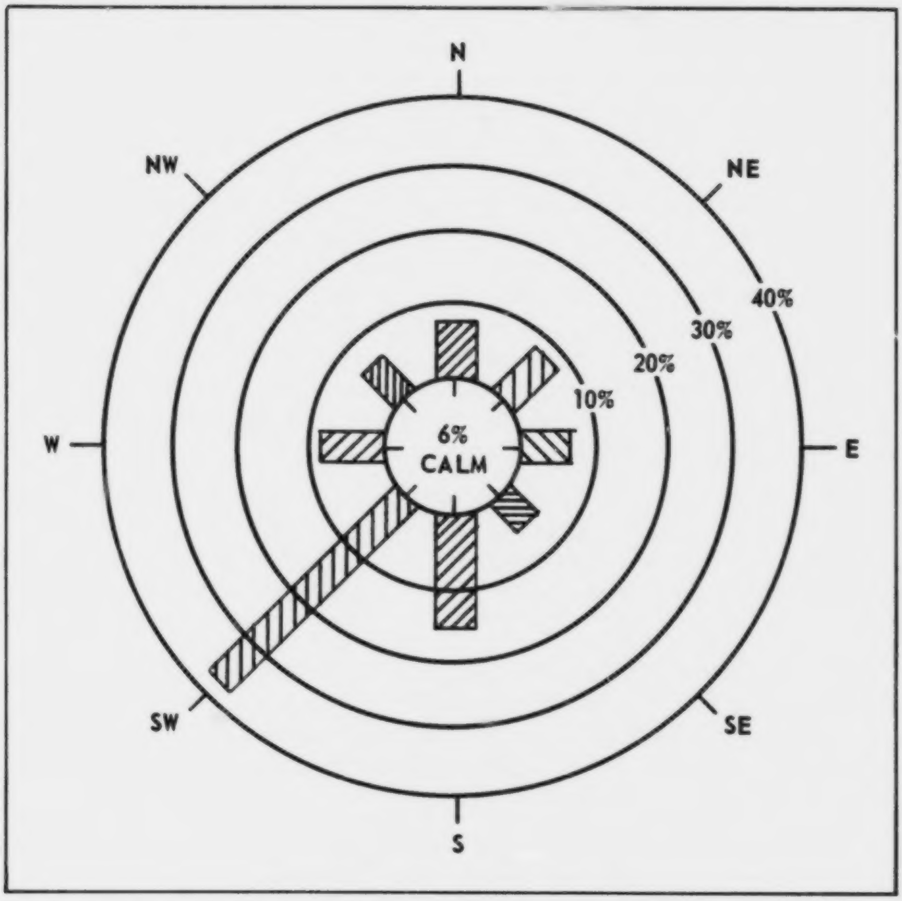

Figure 1. Percentage of wind directions during periods of high pollution, 1957-1959.

These periods of low pollutant levels showed a very consistent weather pattern dominated by high, gusty winds and fresh continental polar air. Most often the weather map showed a low pressure center near the mideast or northeast coast and a high center west of the Philadelphia area. Winds were thus from a direction between northeast and northwest, mostly northwest, with speeds often around 20 mph and gusts over 30 mph.

VENTILATION RATES

The horizontal motion of the air transports pollutants across the city. Contaminants put into the air may be spread out vertically so that surface concentrations will be low if the air is unstable. If wind speeds are high, concentrations will be relatively low because the volume of air into which the pollutants are discharged is large.

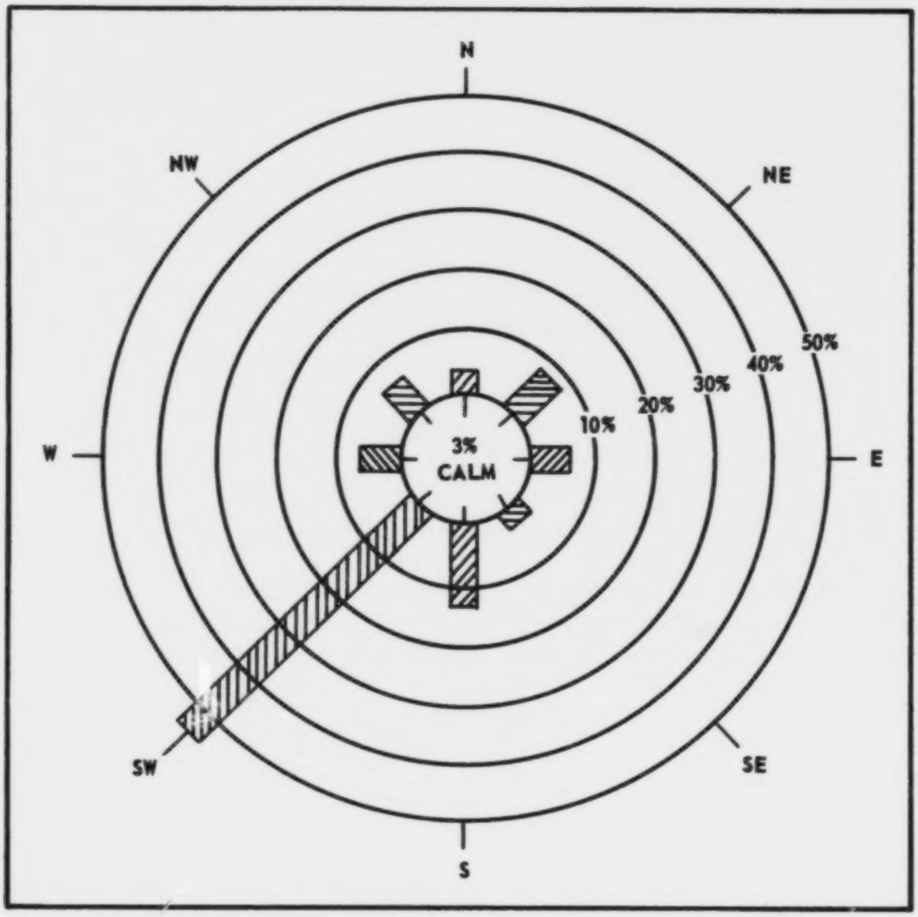

Figure 2. Percentage frequency of wind directions during high pollution periods in the spring season 1957-1959.

If we assume that contaminants put into the air in and around Philadelphia are all discharged at levels below 500 feet and that under stable conditions they remain within that layer, the maximum allowable discharge rates can be estimated crudely for certain wind speeds.

The average wind speed in Philadelphia is between 9 and 10 mph. Wind speeds of less than 8 mph are recorded 37 percent of the time, and speeds of 12 mph or less are recorded 73 percent of the time. On this basis it seems reasonable to use a speed of 10 mph as a first approximation in computing an average ventilation rate. Wind speeds of this magnitude and less are often associated with stable air, but this is not necessarily true during the daylight hours. Thus any assumption that the contaminants are mainly confined in the lower 500 feet is open to question and should be evaluated on the basis of additional data.

In spite of the limiting assumptions it seems worthwhile to consider quantitatively the way in which concentrations of pollutants may be expected to build up in the air over Philadelphia under certain circumstances.

The physical layout of the city is such that an area 10 miles wide and 15 miles long along a southwest to northeast axis should be representative of the surface area to be ventilated. If the contaminants are considered to be concentrated in a 500-foot depth, the volume of air to be ventilated is 14.2 cubic miles. The average rate of generation of sulfur dioxide in Philadelphia is fairly accurately known to be about 830 tons per day. Since most of this is generated in the southern or southwestern to central sections of the city, this seems to be a suitable contaminant to work with in quantitative calculations.

Let us assume that completely fresh air is flowing through our space at a certain rate (the ventilation rate), that sulfur dioxide is being generated in that space at a fixed rate, and that the contaminant is instantaneously distributed throughout the air in the space. Then, the rate at which the total volume of sulfur dioxide in the space builds up with time can be expressed as

$$dV = Pdt - \nu_r \frac{V}{V_a} dt$$

where V = volume of sulfur dioxide in the air at any time
P = rate of production of sulfur dioxide
= 830 tons per day = 2.64×10^{-6} cubic miles per hour
ν_r = ventilation rate in cubic miles per hour
V_a = total volume of air = 14.2 cubic miles.

Note that $\frac{V}{V_a}$ = concentration, C.

For a 10-mph wind speed, the ventilation rate is 9.47 cubic miles per hour, and

$$dV = 2.64 \times 10^{-6} dt - 9.47 \frac{V}{14.2} dt$$

$$\frac{dV}{2.64 \times 10^{-6} - \frac{V}{1.5}} = dt$$

$$-1.5 \ln (2.64 \times 10^{-6} - \frac{V}{1.5}) = t + \text{constant}$$

$$2.64 \times 10^{-6} - \frac{V}{1.5} = Ae^{-t/1.5}$$

Now, at t = 0, V = 0. $\therefore$ $A = 2.64 \times 10^{-6}$, so

$$2.64 \times 10\text{-}6 - \frac{V}{1.5} = 2.64 \times 10^{-6} e^{-t/1.5}$$

and $$V = 1.5 (2.64 \times 10^{-6}) (1 - e^{-t/1.5})$$

To obtain the maximum V, note that as $t \to \infty$, $e^{-t/1.5} \to 0$, so, V approaches 1.5 (2.64×10^{-6}) as a limit. Therefore, after a long period of time,

$$C \approx \frac{1.5 (2.64 \times 10^{-6})}{14.2} \approx 2.8 \times 10^{-7} \text{ parts of } SO_2 \text{ per part air}$$

or, $C = 0.3$ ppm.

It is hardly likely that pollutants would be restricted to the lower 500 feet of the atmosphere when the wind speeds average 10 mph. The expected concentrations would be one-half of the calculated value or less, if the vertical mixing extended through a layer 1000 feet deep or more.

In many of the periods considered earlier the wind speed was recorded as less than 4 mph on many observations. If we calculate for a wind speed of 3 mph, the ventilation rate becomes 2.84 cubic miles per hour and the maximum concentration is 1.0 ppm.

The concentration buildup, of course, is quite rapid in the early stages and then tends to level off, approaching the maximum for any given set of conditions. For example, if we use about half of the maximum concentration for a wind speed of 3 mph; that is, 0.5 ppm, we find that it takes about 4 hours to attain that value. A graph showing the rate at which concentrations build up for a low ventilation rate is plotted in Figure 3. Note that this is based on the assumptions that the air coming into the city is entirely clean and that the sulfur dioxide is restricted to the lower 500 feet of air.

These derived concentrations are in good agreement with observed concentrations of oxides of sulfur in the city. The observed concentrations averaged about 0.15 ppm over the past 3 years, with an estimated rise to 0.5 to 1.5 ppm if these oxides varied with the soiling index during the periods of minimum ventilation.

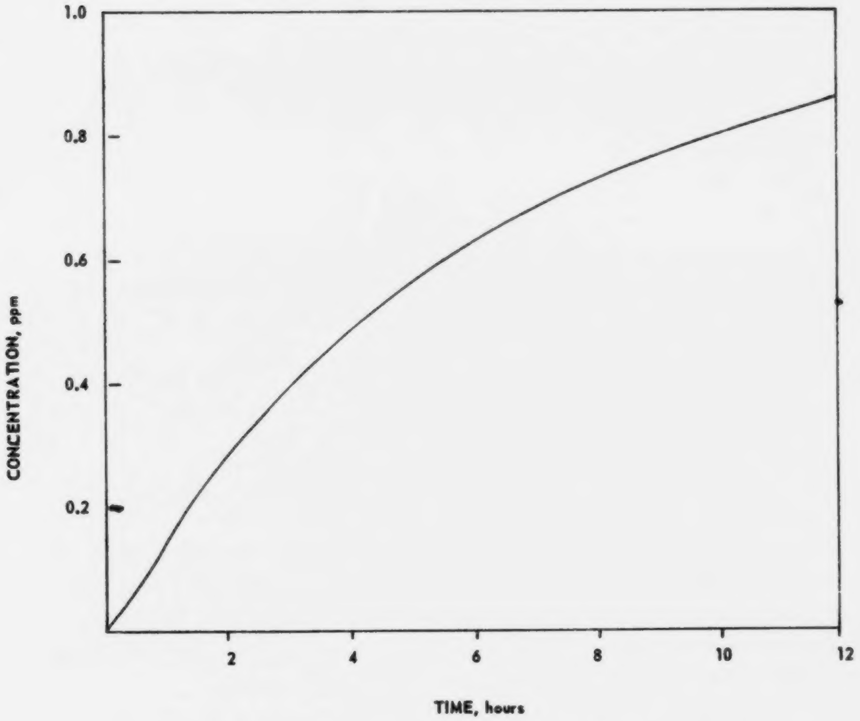

Figure 3. SO2 concentrations versus time for a wind speed of 3 mph.

EXPERIMENTAL FORECAST PERIOD

At the suggestion of Mr. Raymond Smith, Chief of the Air Pollution Control Section, Department of Public Health, of Philadelphia, a short experimental program was set up to predict high pollution episodes for the city. This program embraced the period January 1 through April 30, 1961, but excluded the first 2 weeks in March. During this program we were to alert the City to the probability of high pollution levels at 9 AM at least 24 hours before the dates on which such high pollution levels were expected to occur. We were to issue a definite high pollution level forecast by 9 AM on the date of expected occurrence and to give 24 hours notice of the expected time of relief.

Five air pollution "episodes" were recorded during the experimental program. Four of these were successfully forecast. For two episodes we were able to give 48 hours advance warning, and for the other two, 24 hours. On three occasions we alerted the city 24 hours in advance but cancelled the alert by 9 AM on the alert date. On these dates no high pollution levels were recorded. Thus, periods of high pollution level in Philadelphia were successfully forecast at least 24 hours in advance with 80 percent accuracy.

SUMMARY

Simple air pollution theory indicates that relatively few meteorological and air quality observations are necessary in general air pollution studies. Even these relatively few observations are usually lacking, however, in studies of the behavior and quality of the air over a particular city. The observations of meteorological quantities related to air pollution should be standardized and the number of observations increased. Theory should be extended to include the complications brought about by characteristics of urban areas. At the same time, some useful rules for forecasting and regulating air pollution can be formulated for a city such as Philadelphia on the basis of currently available observational data.

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DISCUSSION

MR. SCHUENEMAN: I wonder if you have an estimate of the additional time it might take a regular weather bureau station operator to make pollution forecasts once he has run through the exercises of developing and selecting parameters. Assuming that he is making forecasts for other purposes, how much additional work would it be?

PROFESSOR DAVIS; As a rough estimate, I think it wouldn't take him any more than an extra 45 or 60 minutes to make a special air pollution forecast for a city like Philadelphia.

DR. SCHMIDT: I was very much interested in the last graph you showed giving the increase of air pollution as a function of time. I just tried to put it in another way by taking the square root of time and I think that you found also that the increase is proportional.

PROFESSOR DAVIS: I made a note of that in the paper you gave, and I am sure that is a pretty close approximation.

DR. SCHMIDT: I wonder if you could briefly tell us how many stations you used in gaining your pollutant levels for Philadelphia. Did you find any great variation statistically between these stations? And were these only particulates, or did you also include the gaseous material?

PROFESSOR DAVIS: We used only two stations in the City of Philadelphia for the reason that over that 3-year period only two stations were making continuous observations. The measurements at other stations were sporadic, and we wanted observations on a continuing basis. These were particulate measurements made with the AISI and the high volume samplers.

DR. SCHMIDT: Was there a great difference between these two stations? Did you reach a mean or an average, or just how did you come to a particular level, a danger level of contaminants in your city?

PROFESSOR DAVIS: We didn't establish a danger level. As a basis for classifying the pollution level as high, we set a purely arbitrary figure: when a reading on an instrument was 1-1/2 times the monthly average. We called this a critical value, but one should not read into this any implication that this level is dangerous to health. I have no way of knowing whether this is a critical value in regard to health.

The samplers at both stations were very consistent, I think, in the over-all readings.

MR. FULKS: I would like to hear something more specific about the type of wind exposure you would like.

PROFESSOR DAVIS: Well, as a physicist, about the best thing you can say is that you would like to get all the data you can. If we could stick an anemometer at every corner, and 50 feet above the surface, and all the way up to 500 feet we would like to do this, but it is not feasible. At this point, I am not sure what is required to really describe the wind flow in a city like Philadelphia.

FROM THE FLOOR: Two related values are the SO_2 level and the soiling index. When one exceeded the limit, did the other exceed the limit? And you talk about 1-1/2 times the monthly average - - which month is that? If that occurs in the beginning of the month, how do you determine what the monthly average is?

PROFESSOR DAVIS: With regard to the second question, the data were furnished me by the City. The Air Pollution Control Section of the City simply averaged all the values from the beginning to the end of the month, and any individual reading that turned out to be 1-1/2 times that average was considered to be a high pollution level.

Now, in regard to your question about the SO_2 values and the soiling index, these values also were given me by the Air Pollution Control Section of the City of Philadelphia. They are confident of their SO_2 levels. They didn't have measurements on a parallel basis, but they assumed that the soiling index followed the same pattern as the SO_2.

MR. ROBINSON: I am concerned about the first statement in your answer. In air pollution studies, I think that one thing we come across is a great deal of variability, both in meteorological and in air pollution measurements. This makes your use of at most two stations questionable. I would like to see you expand a bit on this idea of simple relationships and few measurements.

PROFESSOR DAVIS: Well, I think during the early part of the paper I cited an equation such as those derived by Sutton as the basis for the theory behind diffusion. Now, obviously simplifying assumptions are made with regard to the microscopic condition of the atmosphere and so on, but if you work with equations such as Sutton's and others of similar nature it appears that wind speed, wind direction, and air stability are all you need.

MR. ROBINSON: This is fine in theory, but when you bring these together with your measurements, you don't come up with a situation that makes you very satisfied with just a few observations.

PROFESSOR DAVIS: I thought that was the whole point of my discussion: the theory indicates that only a relatively few observations are needed, but even these are lacking.

DR. NEIBERGER: I only want to comment that the theory is based on very simplified assumptions, which are not ordinarily met in nature, and perhaps this is the difference that you are talking about.

PROFESSOR DAVIS: That's right. That's the only theory we have, I think.

DR. GIFFORD: It is true that Sutton's method involves a number of simplifying assumptions, but I think Sutton would be the first person to point out, were he here, that he never intended that the method that he presented should be applied to the distances comparable with the size of a city, nor to deviations from the smooth, gently rolling land, for which his method was first presented. The fact that it has been applied in these other ways in no way reflects upon the quality of his contribution, which was great.

Very recently there has been a method used in connection with the Atomic Energy applications. That sort of air pollution is restricted at present to isolated or groups of isolated sources. This method has been put forward by many of us, particularly by Mr. Pasquill in England. It avoids the simplifying assumptions by essentially relating the theoretical problem directly to the high-grade measurements of atmospheric dispersion that have been made by some of the people in this room and others in the last few years. This method is compatible with the sort of treatment that Sutton presented. And I don't want to present an uninvited paper at this point, but I would like to say that I will have available for distribution tomorrow, to any of those of you who are interested, a little pamphlet published by the Atomic Energy Commission and my office, the Oak Ridge Weather Bureau Office, which lists the essential technical information that is needed in order to use this method and gives something of the rationale. This pamphlet tells you what observations the method is based on.

The Thermal Climate of Cities*

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Summary

The urban "heat island" and other aspects of the anomalous temperature distribution in cities are discussed. Evidence is presented of the long-term intensification of the heat islands of several U. S. cities, associated with their physical growth. Contributory causes of the heat island are outlined, including local heating plants (winter), insolational superheating (summer), and the influence of aerosol and gaseous pollutants on the urban radiation budget. The influence of the heat island on other aspects of urban climate, such as lapse rate, cloudiness, and turbulent mixing, is briefly considered.

THE URBAN "HEAT ISLAND"

Many familiar urban-rural contrasts of weather and climate are due more or less directly to the fact that cities are warmer than their environs. This characteristic warmth of a city, appropriately dubbed the urban "heat island," is particularly noticeable at night when skies are clear and winds are light. Indeed the "heat island" is so characteristic of urban climate that local Weather Bureau forecasts must usually account for it with such familiar wording as, "clear tonight, low temperature 40° in the city and about 30° in the suburbs. . ."

That certain cities are warmer than their environs has been known for a very long time. London's heat island was documented by Luke Howard[1] as long ago, apparently, as 1818. More than a century later, Vienna's was described in great detail, among others by Wilhelm Schmidt,[2] who in 1927 was the first to use an automobile to obtain thermal cross-sections of a city. Since then, the temperature distributions of many cities have been sampled. The example of Washington, D. C., has been discussed by Landsberg.[3] Undoubtedly the most exhaustive study of urban temperatures yet published is that of Sundborg[4, 5] for Uppsala, Sweden.

Duckworth and Sandberg[6] have recently surveyed the temperature distribution of three Californian communities by automobile. Their study, the most comprehensive of its kind in the United States to date, demonstrated that relatively small towns have heat islands too. One survey, made on a clear spring night, is

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*A revised version of this paper appeared in Weatherwise, vol. 14, no. 6, December 1961

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superposed on a photograph of San Francisco, as shown in Figure 1.

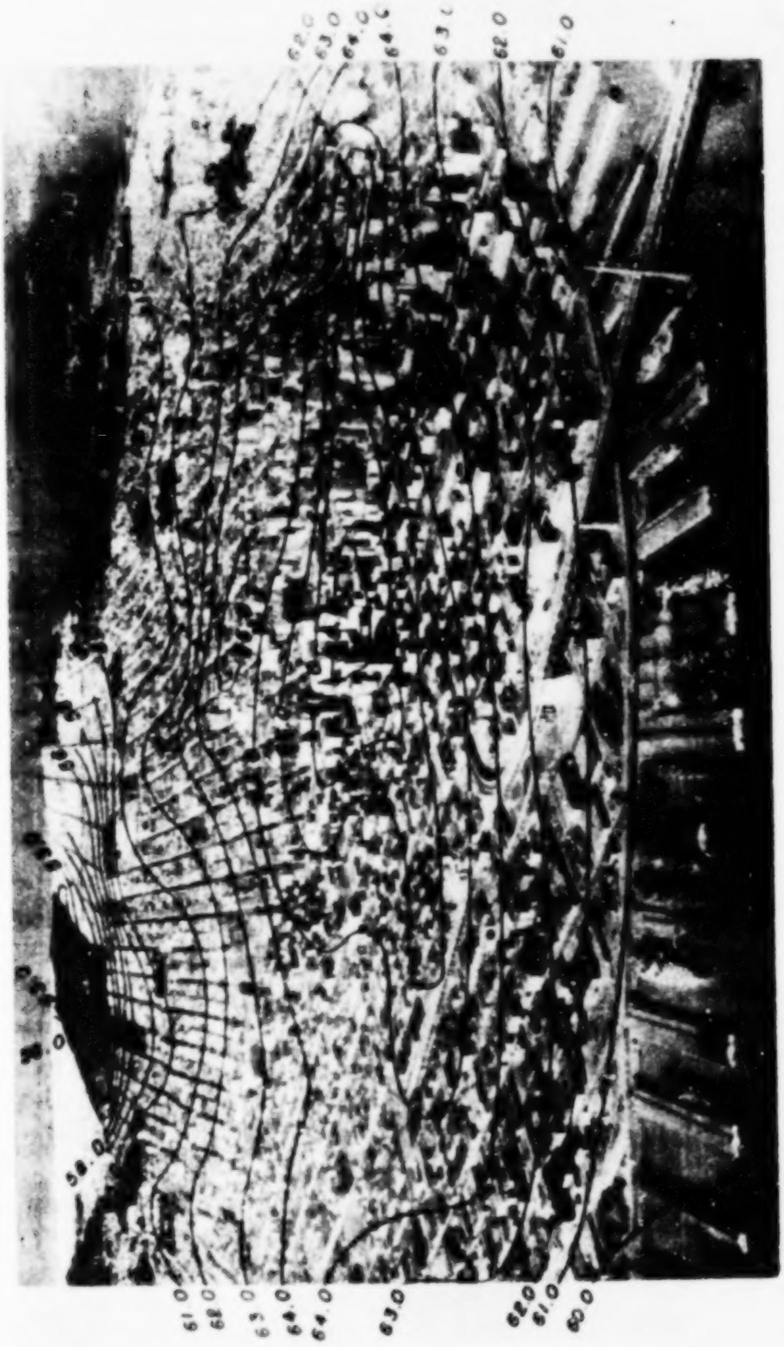
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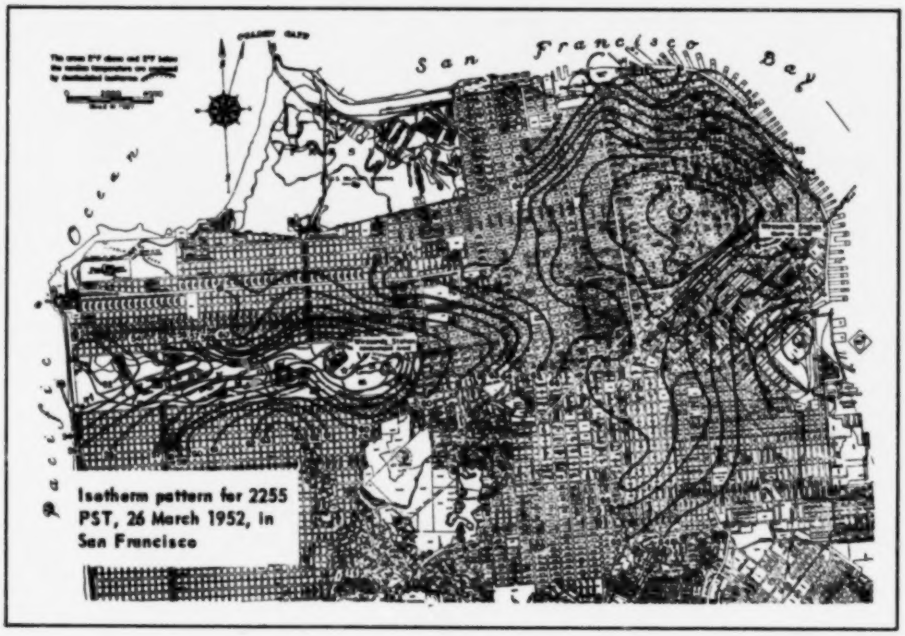
Figure 1. Isotherm pattern for 2320 PST on 4 April 1952 superimposed on an aerial photograph of San Francisco.

Another survey by the same investigators is shown in Figure 2. On these occasions, which were not particularly unusual, the temperature of the densely built-up business district was some 20°F higher than the lowest observed suburban temperature, and 7 or 8°F higher than the average temperature of the urban periphery.



Isotherm pattern for 2255 PST, 26 March 1952, in San Francisco

Figure 2.

IS THE HEAT ISLAND REALLY MAN-MADE?

Most cities were originally settled where they were because of desirable topographical features, such as a river advantageous to commerce or hills tactically valuable in their defense. Such features are certain to produce microclimatic anomalies. Someone, for example, who knows both San Francisco and a smattering of microclimatology, might well look at Figure 1 and reasonably conclude that the same temperature pattern would have existed on the eve of the California gold rush in 1848, when San Francisco was a mere village of 800 inhabitants. After all, the highest temperatures are to be found on Nob Hill, lying above the nocturnal inversion likely to spread over the rest of the city in clear calm weather, and the lowest temperatures are in Golden Gate Park, which at its minimal elevation would be chilled the most under this same inversion.

How, then, can we know that urban heat islands are not topoclimatic anomalies that would exist, city or no city?

First, we can point to the fact that cities in entirely different topographic settings typically possess heat islands. Examples of heat islands in smaller cities, again measured by Duckworth and Sandberg, are shown in Figures 3 and 4.

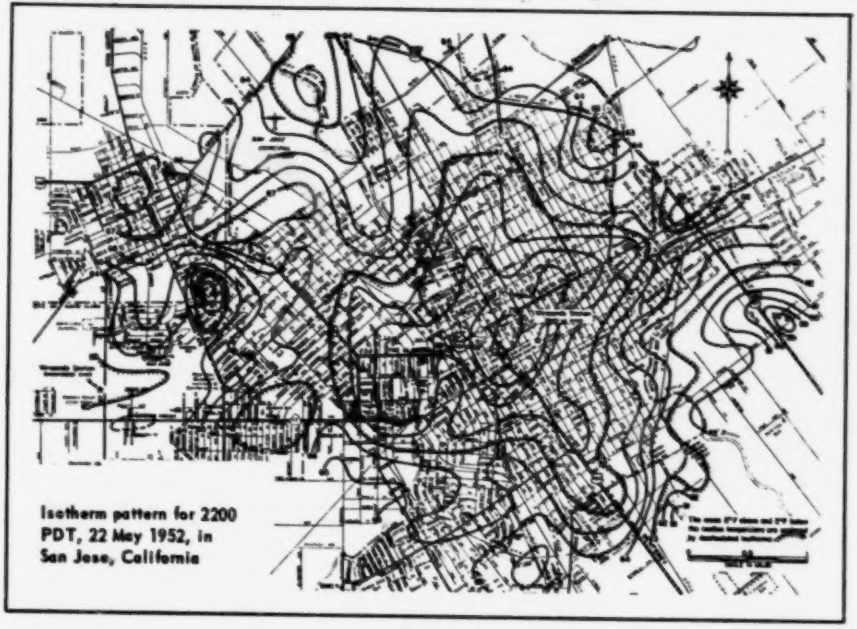

Isotherm pattern for 2200 PDT, 22 May 1952, in San Jose, California

Figure 3.

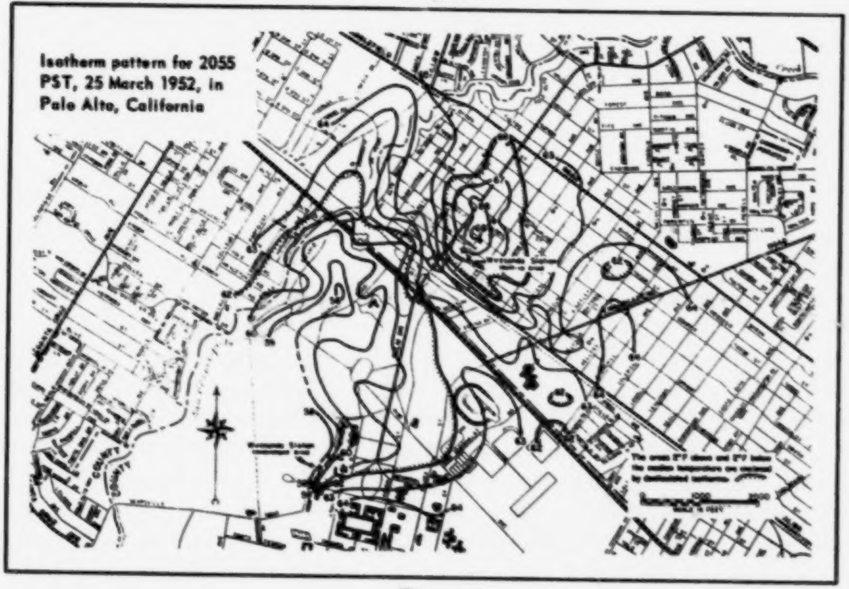

Isotherm pattern for 2055 PST, 25 March 1952, in Palo Alto, California

Figure 4.

Second, we can sometimes demonstrate that the heat island of a city is weaker on Sundays, when the city is comparatively dormant, than on other days of the week, when it is teeming with people and bustling with activity. For example, a comparison of daily maximum and minimum temperatures in the city of New Haven and at its neighboring airport, averaged for four winter seasons, is shown in Table 1. The relative warmth is seen to have averaged only about half as much on Sunday as on any other day. (This result is statistically significant at the 99 percent level.)

TABLE 1

EXCESS WARMTH OF CITY COMPARED WITH AIRPORT (F°)

Data for New Haven, Conn., in Four Winter Seasons 1939 - 1943

Day of week	Maximum temperature	Minimum temperature	Mean daily temperature
Sunday	0.1	1.2	0.6
Monday	0.0	2.0	1.0
Tuesday	0.2	2.4	1.3
Wednesday	0.0	2.1	1.1
Thursday	0.0	2.3	1.2
Friday	0.0	2.4	1.1
Saturday	0.0	2.1	1.0

Third, it is frequently possible to show a gradual increase of the intensity of an urban heat island as the city grows in size and population over the years.[8] Examples are Washington, D.C. and Baltimore, Md., whose seasonal mean temperatures as measured at their downtown Weather Bureau stations, are shown in Figure 5 in the form of 10-year moving averages from 1894 to 1954. For comparison, the combined temperature series for a large number of rural climatological stations, all within about 50 miles of these cities, is also shown in this figure. One can see that, especially in the summer season, the cities have been gradually warming up in relation to their rural surroundings. Curiously, this relative warming has been almost entirely absent in winter (see bottom of Figure 5).

The rates at which ten cities in the eastern half of the United States have warmed relative to their environs since the 19th Century are compared for each season in Table 2. Here, the cities have been ranked in order of growth rate, measured by each city and its suburbs. Such a measure of city growth has been used because it approximates the average length of travel

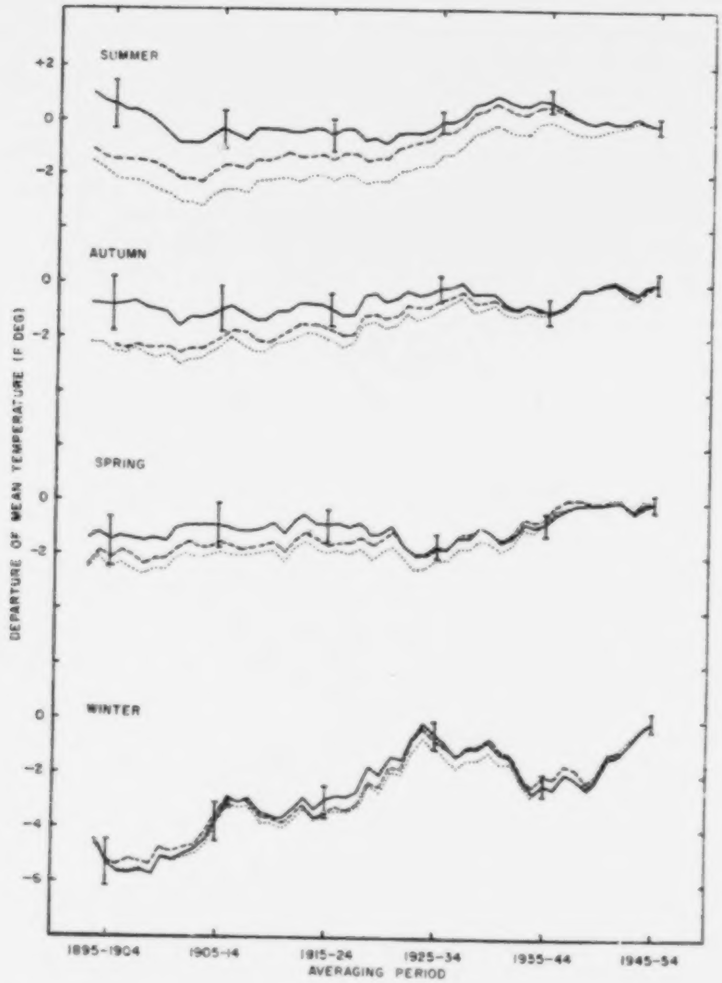


Figure 5. Ten-year moving averages of seasonal mean temperature in eastern Maryland, shown as departures from 1945-54 average. Solid curve is average of data for 17 rural cooperative stations; dashed curve is Baltimore city data; dotted curve is Washington, D. C., city data.

over the city of air arriving at the Weather Station thermometer and the total urban heating is assumed to be proportional to this travel distance. Table 2 shows that the highest rates of urban warming generally are associated with the most rapidly growing cities. The relationship is close in summer, as shown in Figure 6, but not nearly so close in winter or for the year as a whole. A different measure of city growth would apparently be more appropriate in the colder half of the year, when the urban heat island is maintained by different kinds of heat sources than those prevailing in summer. We will have a little more to say about these presently.

TABLE 2

RATES OF URBAN WARMING OF SELECTED CITIES, BY SEASONS

(Excess over Rural Environs)

(All values shown are significantly different from zero at 99 percent confidence level)

City	Period of record[a]	Growth rate index[b]	Urban warming rate (degrees F per 100 yrs)			
			Winter	Spring	Summer	Autumn
Cleveland, Ohio	1895-1941	12.9	1.8	3.8	5.1	2.7
Boston, Mass.	1895-1933	10.5	2.9	3.2	4.7	3.7
Washington, D. C.	1893-1954	9.9	c	1.5	4.3	2.7
Tampa, Fla.	1895-1931	6.6	4.8	2.6	2.9	3.4
Baltimore, Md.	1894-1954	6.0	c	2.0	3.0	2.7
Charlotte, N. C.	1897-1951	5.1	c	c	1.7	c
Rochester, N. Y.	1914-1940	4.5	c	c	c	c
Nashville, Tenn.	1897-1948	3.0	c	c	c	c
Lincoln, Nebr.	1895-1954	2.4	c	c	2.2	c
Marquette, Mich.	1899-1954	0.6	c	c	c	c

[a] Limited to period of available city-office data only.
[b] Rate of change of root population (units per year).
[c] Not significantly different from zero.

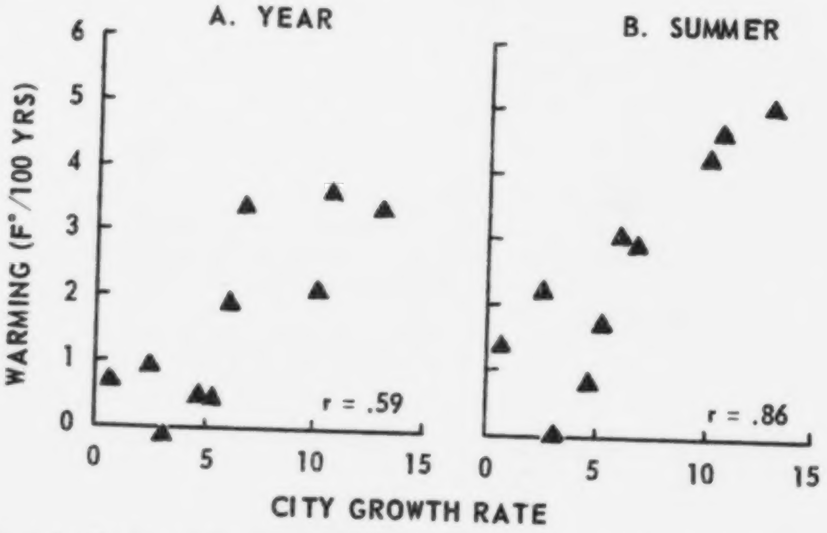


Figure 6. Change of urban temperature with city growth: annual mean temperature on left, and summer-season mean on right. Cities are those listed in Table 2. "r" is correlation coefficient.

In an earlier study along similar lines,[7] I compared the net temperature changes between the 20-year periods 1900 through 1919 and 1920 through 1939, at a total of 77 cities throughout the United States, with the corresponding changes of square root of urban population. Regression lines were fitted to these data in each of six geographical sections of the country. For the annual mean temperature, the results are reproduced in Figure 7. In all six zones the regression lines have a similar slope, an indication that the more rapidly growing cities in each zone tended to experience faster rates of warming than the slower-growing cities. This result is quantitatively as well as qualitatively consistent with the more direct measure of the effect of urban growth in 10 cities shown in Figure 6.

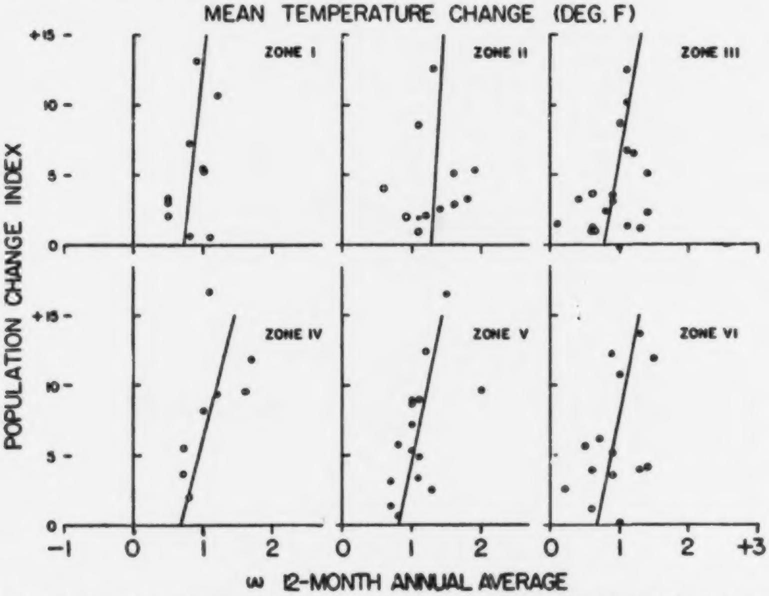


Figure 7. 20-yr changes of annual mean temperature at 77 selected cities in the United States, as function of 20-yr changes in square root of their urban population, by geographical zones. Computed regression lines are included. Data cover period 1900 – 1939.

CITY-RURAL TEMPERATURE DIFFERENCES IN RELATION TO TIME OF DAY

It has already been mentioned that the urban heat island is most evident at night. Figure 8 shows comparative monthly average temperature in the center and at the edge of a city for each hour of the day. The figure refers to Vienna, Austria, for which hourly mean temperatures are readily available,[9] but there is no reason to doubt that data for American cities would show similar comparisons.

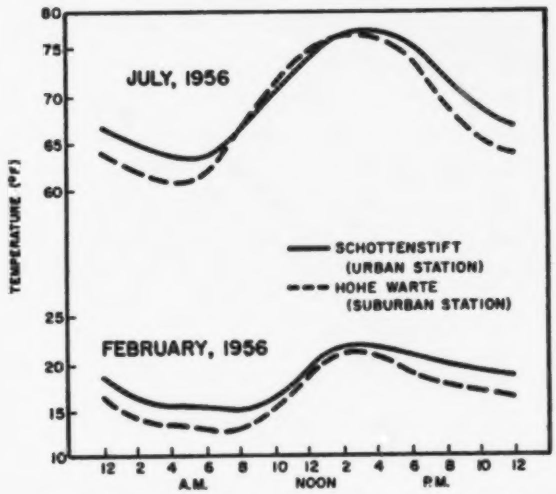


Figure 8. Diurnal variation of temperature in Vienna, Austria.

In July the relative warmth of the city is greatest at night, and virtually absent during most of the daytime. In fact, during mid-day in summer, it is not unusual for the city to be a fraction of a degree cooler than its environs, owing presumably to the attentuation of sunlight over the city by dust and smoke. The city continues to hold its heat in the late afternoon, after temperatures have begun to slide in the suburbs. Maximum daily temperatures in the city may thus be reached an hour or two after they are reached in the suburbs. Minimum temperatures are also reached somewhat later in the city, and the daily temperature range is smaller.

In February (the coolest month of the year in Vienna) the city tends to remain warmer than its suburbs both day and night. Again, the daytime differences are smaller than the nighttime ones. Daily maxima and minima of temperature are reached slightly later in the city than in the suburbs, and the daily range is less in the city.

CITY-RURAL TEMPERATURE DIFFERENCES IN RELATION TO TIME OF YEAR

Figure 9 shows two examples of the annual march of temperature in and outside cities. Comparative monthly normals of daily maximum, mean, and minimum temperature are included in this figure. These examples are typical in showing the urban heat island to be reflected most in minimum temperatures, and least in maximum temperatures, throughout the year.

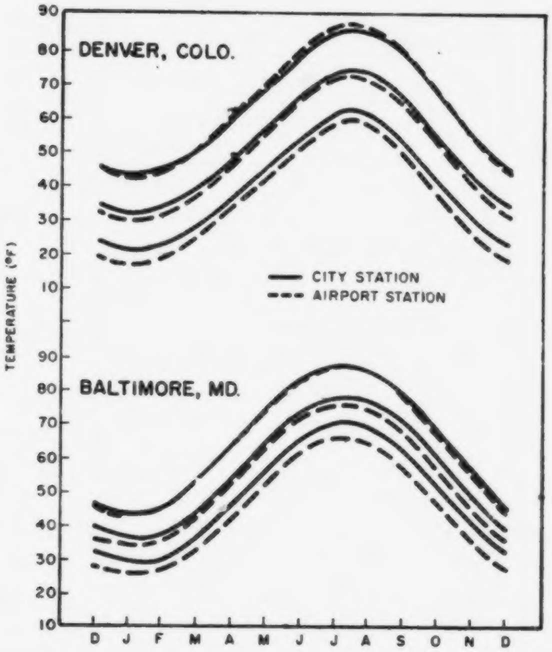


Figure 9. Annual variation of average monthly maximum, mean, and minimum temperatures in and outside selected cities.

CONTRIBUTORY CAUSES OF THE HEAT ISLAND

Various physical factors are probably responsible in part for the formation of urban heat islands. Some are more influential in summer, and others more so in winter.

On a summer day solar radiation is more or less readily absorbed in the city by building and paving materials possessing large heat-storage capacities. There is virtually no vegetation or moist soil that can soak up some of this solar heat by evaporation, as it does in the country. The temperature of streets and south-exposed building surfaces may soar well above 100°. Even though air temperatures may be reasonably low, these hot surfaces irradiate us poor pedestrians, seemingly like so many turkeys in a slow oven! To make matters worse, the buildings obstruct ambient wind that might otherwise offer relief.

As night falls, the streets and buildings begin to cool down, but very slowly. Their radiation continues all night, and their elevated temperatures prevent the air itself from cooling as much as it otherwise would. By morning this heat has still not entirely expended itself, and the next sizzling day begins with this thermal handicap.

On a winter day matters are a bit different – at least in our relatively high latitudes. The solar rays may have appreciable heat in them, but the streets and buildings are warmed perhaps as much by the furnace heat of our office buildings and homes. This heat seeps through their imperfectly insulated walls and windows and disgorges through countless rooftop chimneys.

During the day the atmosphere is comparatively turbulent, and the urban warmth is dissipated before street-level temperatures can be much affected. By nightfall, however, the furnaces begin to work harder against the cold, and the increasing sluggishness and stability of the atmosphere allow their heat to accumulate more readily in the city. In addition, the smoke, water vapor, and carbon dioxide escaping from the chimneys spread out in a "blanket" above roof-level that supplements the building walls themselves in intercepting some of the heat radiation from the streets and re-radiating part of their own heat downward. Under these circumstances temperatures remain relatively high in the city throughout the night, all the way from street level to heights often considerably above the roof tops.[6]

Surmounting this warm layer, a nocturnal inversion is commonly encountered. This inversion inhibits the upward dispersion of smoke and other pollutants in the city. In fact, the inversion may become intensified by the pollution layer whose upper surface cools by radiation to the sky, just as in the country the ground itself cools by radiation. This, in turn, promotes the further increase of pollution concentration in the city, until arrival of morning, when the sun's heat can finally destroy the inversion.

EFFECT OF WEATHER ON THE HEAT ISLAND

In the preceding discussion, we have been presupposing average weather conditions, characterized by relatively clear skies and light winds. Since cloudiness and strong winds would inhibit the formation of ground inversions, and since wind speed would also affect the rate of "ventilation" of the city, it is to be expected that the intensity of the urban heat island would depend substantially on these weather variables. Sundborg,[4] who studied the matter in some detail for Uppsala, found that the nighttime urban-rural temperature difference, D, could be roughly approximated by an equation of the form

$$D = \frac{a - b\,N}{V}$$

where N is percent cloud cover, V is wind speed, and a and b are constants. Undoubtedly such a formula could be used for cities other than Uppsala; appropriate values of the constants would depend on the city and on the locations of the wind speed and comparative temperature measurements. *

In this discussion it has been possible merely to sketch in some of the salient characteristics of the urban heat island. Much remains to be done in establishing the relative importance of the various physical factors involved. Of particular interest to us here, of course, is the role of atmospheric pollution— water vapor and carbon dioxide as well as smoke— in altering the radiative heat balance of cities. Unfortunately very few theoretical studies of this subject have been made. We hope that this matter will receive much more attention in the near future.

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* Note that calm winds would have to be treated as a special case case (in Uppsala, calms were rare). Sundborg also found that temperature and humidity influence D somewhat. At night, however, these factors are negligible in comparison with wind and cloudiness.

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DISCUSSION

MR. MILLER: I have two points. One is the possibility that Washington, D. C. is different from other cities as to the limitation on vertical construction. I am not talking about the growth of the government, but the buildings.

Second, I would like to have Dr. Mitchell comment on what geographers are calling "strip cities," such as the urban complex between Cleveland and Pittsburgh, or between Washington and New York.

DR. MITCHELL: Well, the government in Washington is certainly growing, but mostly it is growing in the suburbs. As a matter of fact, looking at the horizon from 24th and M Streets, where the long series of observations cited here were made, I am impressed by the fact that it doesn't differ very much from what it looked like in photographs 20, 30, or 40 years ago. I think that in winter, at least, the intensity of the heat island, from the point of view of a single spot in the city, is importantly affected by what is happening right in the local area, not so much by what is happening at the distance of the suburbs.

Another way of saying the same thing is that in winter, at least, the heat island will grow in area with the growth of a city, but will not intensify much in terms of its central superheating value. But in summer apparently other things are involved -- what is going on in the suburbs does affect temperatures downwind in other parts of the city.

Now, concerning these "strip cities," I don't really know what can be said about them. Apparently, even a moderately small amount of human development is enough to affect temperatures, and especially in winter it doesn't take very much development to affect temperatures quite noticeably. From that point on, further physical development will have a relatively small effect on temperature. So I think that if I were to predict how temperature conditions in strip cities and other newer rural developments would change, I would expect to find initially a rather rapid increase of nocturnal temperatures in these areas. Then, as these communities continue to grow, in a peripheral sense, the effect will probably become less pronounced.

MR. ROBINSON: I think somebody should speak from Palo Alto.

I noticed something on the slides that I hadn't noticed before, and perhaps it is significant. The temperature differences from San Francisco to Palo Alto were not great in the sense of the built-up part of the city, each case being in order of 10 degrees. But the area covered by this high-temperature isotherm was primarily, if my memory serves me rightly, the area in which we have reinforced concrete buildings. In Palo Alto, this is an area of a few square blocks; in San Francisco it is possibly about a square mile, or maybe 2 square miles. The area for San Jose would be in between. But if this is a factor, perhaps, in the growth of cities, the development of the downtown area and the growth of reinforced concrete construction is a significant factor, and then, perhaps, the central portions of the city have seen the maximum as far as this is concerned. I noticed, that for Palo Alto there was a slight indication of an isotherm even around the building complex of Stanford University. This, again, is a stone and concrete group of buildings in an isolated, really a rural setting. This might also be a factor of difference to look for if careful observation should come about between an eastern city with brick construction in the homes and residential areas, compared to a western city with wood and stucco, that retains much less heat.

DR. GIFFORD: One of the graphs you presented showed the gradual increase of the winter temperature in Washington. I recall that in the climatology that I took some time ago, we considered an over-all temperature increase for the whole world. I wonder if you could comment on the effect of this city heat island phenomenon on the possibilities of detecting an over-all worldwide temperature or of defining an overall worldwide temperature? Since this increase is apparently an urbanization effect, could we now know actually what the global temperature is doing?

DR. MITCHELL: I think so. You may remember that I showed a series of six regressions of the temperature trend versus the population growth of the cities. (Figure 7) The point at which these regression lines intersect the zero line of city growth was not at zero temperature change. This is one indication that there is a residual trend that is certainly due to large-scale climatic variations. Taking records from various nonurbanized locations we come to the same conclusion, that definite temperature trends exist over and above what the cities are contributing. The two effects are very real, and for many purposes it is essential to separate the two; that's what I tried to do here.

DR. GIFFORD: Are these trends of about the same magnitude?

DR. MITCHELL: That depends on what time interval you consider. They have been about equal since the turn of the century, yes. This was only a coincidence.

Mr. STOUT: Mr. Changnon has some data on thermograph records from the four stations around Champaign-Urbana, a small city with a population of 7,000. The interesting thing is that we do have the cooling off at night, which you would expect at the rural stations. But in the afternoon these stations are warmer than the downtown stations. So there is sort of a ring, or a donut effect taking place, in the afternoon, anyway, that I have no explanation for.

DR. HILST: Has any attempt been made to use these data to determine the thermal energy excess in the heat island and compare this with the energy consumption in the city?

DR. MITCHELL: You mean to make direct calculations of the amount of warming to be expected from local fuel consumption? Did I understand you correctly?

DR. HILST: Just what do these numbers represent in the way of excess thermal energy in the atmosphere?

DR. MITCHELL: They are quite consistent with estimates of the heat produced by fuel combustion in the winter seasons. I can cite a few studies, but they put a highlight only on this matter of fuel consumption and not other heat-budget factors involved.

Some Observations of Cloud Initiation in Industrial Areas

GLENN E. STOUT, *Head, Meteorology Section, Illinois State Water Survey, Urbana, Illinois*

Summary

A petro-chemical industry, located in the rural areas of central Illinois, has been observed to initiate clouds. At least five cases are partially documented by surface, airborne, or radar observations. On one occasion a cumulus congestus cloud formed and produced tornado funnels. No other clouds were present in the area. Other cases are discussed and the available data presented. Preliminary occasional observations suggest that this industrial source could be used for an interesting research study of the possible influence of industrial pollution on cloud formations.

Various investigators have suggested that pollution from industrial sources enhances precipitation. To the best of my knowledge, no one has proposed that pollution decreases rainfall downwind from the source. For example, Landsberg and Changnon, in earlier papers of this symposium, have suggested that precipitation over an urban area is greater than over the rural areas. To test a hypothesis that nuclei from specific industrial sources might increase precipitation in the atmosphere, the staff at General Electric Company, Falconer and Schaefer,[1] studied rainfall patterns downwind from lead-smelting plants in the West. Results were inconclusive, since the lack of sufficient rain gages in the area prevented a comprehensive study.

More recently, F. W. Van Straten,[2] of the U.S. Navy, proposed that carbon black would produce clouds under certain conditions and would enhance the development of clouds. Tests were made by spreading carbon black in warm maritime air. Although there was some suggestion that clouds could be produced, the program has not been fully tested.

Telford,[3] of the Commonwealth Scientific and Industrial Research Organization in Australia, recently concluded that a portion of the freezing nuclei in the atmosphere comes from certain types of industrial activity. The smoke from a steel factory was identified as a prolific source. He also concluded that other industries probably have little influence on the freezing nuclei count. It is quite possible that some may produce inhibiting agents.

Studies of rainfall in Illinois by Huff[4] have suggested that the greatest frequency of heavy rainfalls occurred east of St. Louis, Missouri. The annual mean rainfall at Edwardsville,

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Illinois, has increased by 10 percent in the last two decades. A detailed climatological study has shown a higher incidence of fronts in this region. Therefore, the increase may be due to pollution or frontal stagnation.

The rainfall patterns east of Chicago have been of considerable interest to us. For example, LaPorte, Indiana, shows an average annual rainfall of 50 inches, while nearby stations report 36 inches. Correspondence with the State Climatologist of Indiana has not produced a satisfactory explanation of this great rainfall anomaly.

The large concentration of steel mills around Gary could very well support the high incidence of rainfall at the LaPorte station. Figure 1 shows the annual precipitation for LaPorte, Valparaiso, South Bend, and Whiting, Indiana. The increase in precipitation beginning about 1922 is quite evident at the three stations in operation at that time. The continuing increase in the

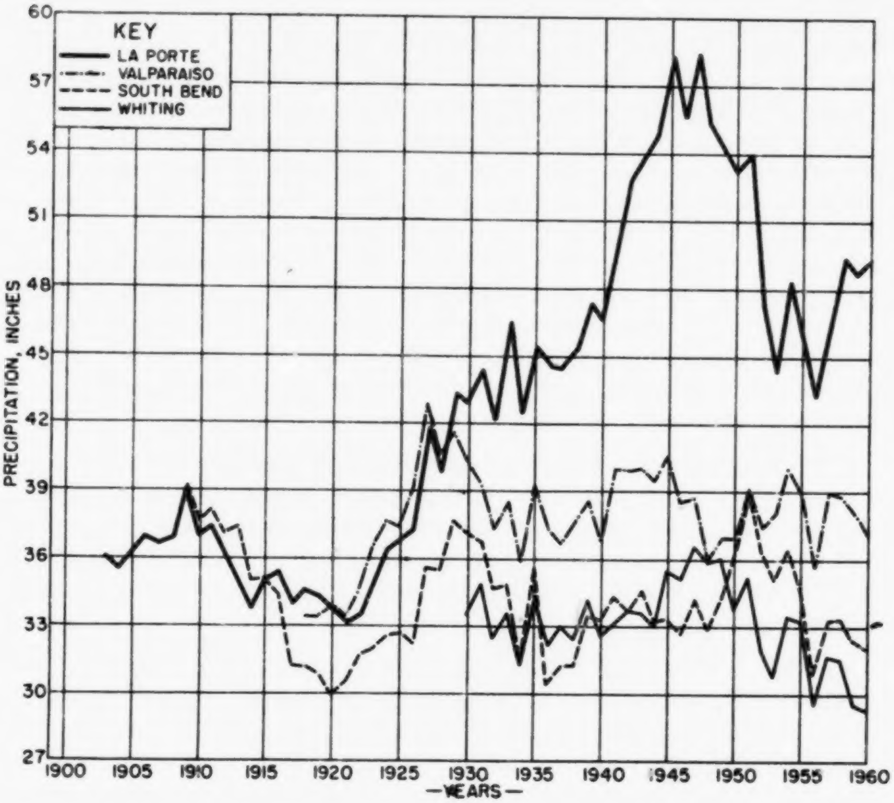

Figure 1. Annual precipitation values determined by averaging 5-year moving totals for selected Indiana stations

annual precipitation at LaPorte is quite striking. Either the exposure of the gage or the pollution from the steel mills has contributed to the anomaly. The LaPorte observer convinced the author that there is an unusual wintertime snowfall belt in a small area around LaPorte. The heavy snowfall arrives with northwesterly flow, which may be due to lake effect. The pronounced increase in rainfall in summer is difficult to explain. Figure 2 shows the annual steel production in the Chicago and Gary industrial complex. The great increase in annual rainfall after 1933 coincides with the greater increase in steel production. Exact figures for the Gary steel manufacturing complex were not available. We have also looked at the rainfall patterns downwind from other industrial areas such as Peoria, Illinois, and find no anomalies of any significance. There are no steel furnaces in the Peoria area.

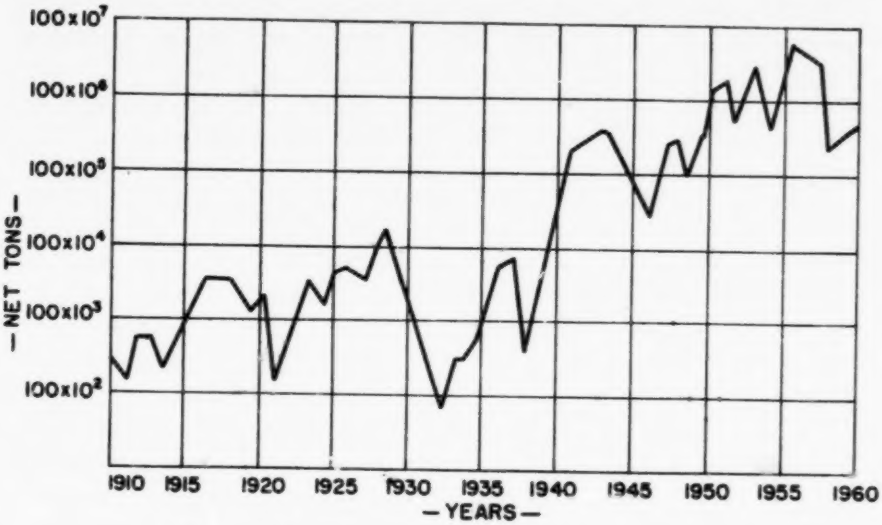

Figure 2. Annual steel production in tons, 1910-1960

Johnson[5] reported that a cumulus cloud developed over a prairie grass fire. The radiosonde data did not indicate any convective activity possible. He thought that the water vapor for the cloud over the fire came from evaporation of the moisture from the green grass, from the top layers of the ground, and also from the combustion of the grass. Hoddinott[6] reported observing a funnel cloud that was due to an industrial activity. He reported that the area of Chester, England, has been a beehive of industrial activity since 1955 and that new cumulonimbus developments were often observed downwind from the steel works of Chester.

The flat prairie land of east central Illinois was transformed from an agricultural area by the construction of a large industrial activity just west of Tuscola, Illinois, in about 1951. The industrial complex is now valued at $130 million and covers approximately a square mile. Five hundred thousand cubic feet of natural gas is used daily in the extraction of various elements including ethane, which is the main raw material used in making petrochemical products. The plant also houses the largest unit in the world for making industrial alcohol.

On December 24, 1954, the Midwest area was under a large, high-pressure system of continental origin. At around 1600, I observed from our laboratory a low stratus-type cloud, the only cloud in the sky, directly south of the airport. There was also one small cumulus turret evident. I drove 20 miles south to the source of the cloud and observed that the stratus was actually a dark smoke cloud below an inversion of 1700 feet. The white cumulus turret was located near the power plant stacks and extended several hundred feet above the inversion. Fallout was occurring about three miles from the stack. Upon investigation of possible contaminations in the air, I learned unofficially that there had been a burnoff of alcohol prior to my first cloud observations.

On March 7, 1960, clouds of unusual origin were again observed near Tuscola and at Decatur, approximately 30 miles due west. A pilot reported that these clouds were the only ones present. Clouds formed near the top of the inversion layer and were approximately 200 feet in depth. Below the base of the clouds, industrial smoke was clearly visible and seemed to be feeding into the cloud formation.

In May 1960, Dr. B. Vonnegut from Arthur D. Little, Inc., and I observed a low-hanging white cloud in the area of the industrial activity in the late evening. A squall line had passed the area in the late afternoon. The industrial cloud extended 15 to 20 miles from the source and was intense enough for radar detection. The top of the cloud as determined by radar was about 6000 feet. No rainfall measurements are available to verify a precipitation mechanism within the storm.

Our most striking observation occurred on May 27, 1960. As we drove to work at 0700 CST, we observed one large cumulus cloud about 20 miles south of the airport. There were no other clouds present within visible range. We immediately dispatched an aircraft, which at that time was outfitted to collect samples of the particulates in the atmosphere, to investigate. As the observer approached the area, he called back to report a funnel hanging from the base of the cloud. In the meantime, radar observations indicated the cloud top was 20,000 feet. A few minutes later, the state police called to report funnels from this isolated cloud. They observed five funnels during the 75-minute period of observation. The particle concentration within the cloud was of sufficient quantity and size that again the radar was able to detect it. To the best of our knowledge there was no precipitation from the cloud. This observation appears to be similar to Hoddinott's in Chester, England.

On October 12, 1961, clear skies prevailed over East Central Illinois except for intense smoke layers over the cities and the Petro Chemical Company area, where inversion around 2500 feet produced a dense smoke layer extending westward from Tuscola. At the same time, a lower inversion with a top at 100 feet trapped a white hygroscopic smoke, which appeared to be a fog layer. This layer extended northeastward from the Tuscola area for approximately 20 miles.

Two types of data should be explored for further study of this phenomenon. First, a radar climatological study of the existence of echoes in and downwind of industrial areas should be undertaken. Secondly, the use of TIROS cloud data would help to support some of these findings.

Wilk[7] of the Illinois State Water Survey has been using well-calibrated quantitized radar information to determine the areas of greatest radar reflectivity during hailstorms. During several of his case studies, he has noticed that the strongest echoes from precipitation masses occur over industrial areas. On other occasions he has observed new echo developments ahead of squall lines downwind of industrial areas such as St. Louis, Missouri. No quantitative comprehensive study has been undertaken to date, but the significance of the data suggests that such work should be performed.

Satellite information also provides a new source of data. Inspection of TIROS photos has on several occasions shown increased cloud activity just east of Gary, Indiana. Maps of rainfall showed localized rainfall in the area during the approximate time ot the satellite passage. Therefore, a climatological study of aerial cloud photos in and around major industrial areas with and without other influences, such as large bodies of water, would prove most interesting.

I have tried to illustrate that industrial complexes produce clouds and enhance precipitation. Conversely, there is always a chance that pollution will have no effect on the precipitation process. Several techniques have been suggested for future data collection and research on the influence of industrial activities on precipitation.

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DISCUSSION

DR. NEIBERGER: Just one or two comments about some experiments that Dr. Dessens in France has been conducting on the French side of the Pyrenees. He has been conducting what he calls a meteorotone, which consists of a square of oil burners about 100 meters square. I have forgotten the amount of oil that is consumed and the corresponding amount of energy produced, but in his experiments under appropriate conditions the smoke column, or the column of heat, develops convective activity to the extent that cumulus clouds are formed. In two or three cases he has had funneled clouds developed which had quite intense rotations, corresponding to small tornados.

MR. KALSTROM: May I ask in what direction these funnel clouds were in relation to the plant and the heat sources -- how far downwind? Or were they quite close to the energy?

MR. STOUT: They were downwind and about 5 miles away. But the cloud kept moving away, so that at the end of an hour the cloud was about 25 miles from the source. It was a slow-moving cloud, but it did migrate away from the source.

MR. KALSTROM: The funnels occurred some distance away from the heat?

MR. STOUT: Yes, that's right.

FROM THE FLOOR: I might mention a rather well-documented case, I believe in the 1920's. An oil fire was reported, where tornados actually occurred.

Session 2: The Dispersion and Deposition of Air Pollutants Over Cities

M. NEIBERGER,* *Chairman*

Summary

In setting limits for the control of pollution sources in industrial and urban complexes, limits must not be established solely on the basis of individual stacks and plants; the basic concept must be the area-source strength, in terms of total emissions per square mile, since the emissions from separate stacks and plants are additive as the air moves across them toward residential and commercial communities. The dispersion of pollutants from vehicle exhausts along congested streets and roads deserves attention. Such questions as the influence of heat from motors and the motion of the vehicles need examination. Studies of dispersion have generally assumed flat uniform terrain and wind conditions in which the direction is steady and the average speed is high compared to turbulent fluctuations. Studies must be performed on the dispersion of pollutants over an irregular complex of buildings and under the influence of wind conditions in which the average speed is low and the magnitude of windspeeds in fluctuations is as great or greater.

In introducing this session on the dispersion and deposition of atmospheric pollution over cities, I want to point out the questions I regard as most important in the consideration of the dispersion of air pollution over cities. For the most part I shall leave the answers to the other members of the panel insofar as answers are known, and to further research insofar as they are not. It is my hope that in the course of this morning's session the foundation for this afternoon's program on present and future needs for observational data will be laid. At the same time, the needs for future theoretical studies will be developed.

In the past almost all studies of the dispersion of pollution have dealt with point sources, and line sources have been considered occasionally. The problem of area sources, and particularly the effective evaluation of how the concentrations due to self-contamination within large source areas depend on the various contributing factors, has begun to be investigated only recently.

We can get a simple indication of this dependence by making the assumption, as is frequently done, that the flux, F, of a contaminant of concentration C in any direction is proportional to its gradient in that direction.

$$F_z = -A_z \frac{\partial C}{\partial z}; \quad F_x = -A_x \frac{\partial C}{\partial x}; \quad F_y = -A_y \frac{\partial C}{\partial y} \qquad (1)$$

Here F_z is the flux in the vertical of a contaminant of concentration C, and A_z is the coefficient of proportionality, ordinarily called the coefficient of turbulent exchange, or sometimes the eddy diffusivity.

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F_x and F_y are similar expressions for the flux and in x and y directions.

As is familiar to all of you, consideration of the convergence of this flux leads to the expression for the rate of change of the concentration with time given in equation 2.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(A_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_z \frac{\partial C}{\partial z}\right) \quad (2)$$

For an individual point source, integration of this equation leads under simplifying assumptions to the formulas of Roberts, Bosanquet and Pearson, and Sutton.

In a general way their formulas show the concentration at the ground downwind of a large elevated source in the form shown in Figure 1. The position of the large elevated source is taken at the origin of the coordinate axis; the maximum ground concentration is some distance downwind because of the time that is required for the diffusion to carry the pollutant down to the ground, and the further diffusion spreads it out so that beyond this point along the plume axis you have a more or less exponential decrease.

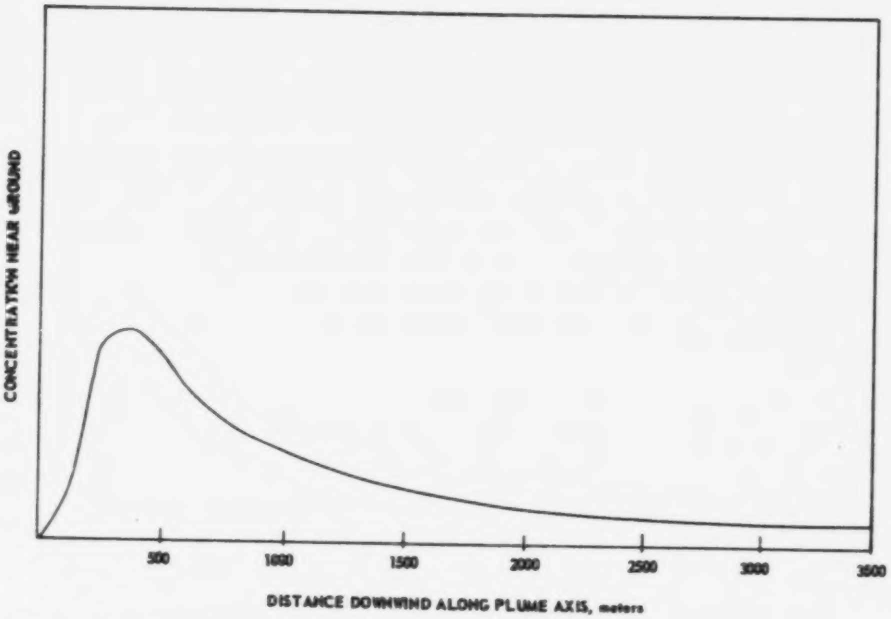

Figure 1. Variation with distance of surface concentrations from elevated source (schematic).

Now, if you had initially a background of pollution on which the contamination due to this source is superimposed, you would have the situation shown in Figure 2. Here the background concentration is shown by the dashed line and the total concentration is shown by the same curve as in Figure 1 displaced upward. Far enough downwind of the point source, the effect is simply to increase the background concentration slightly.

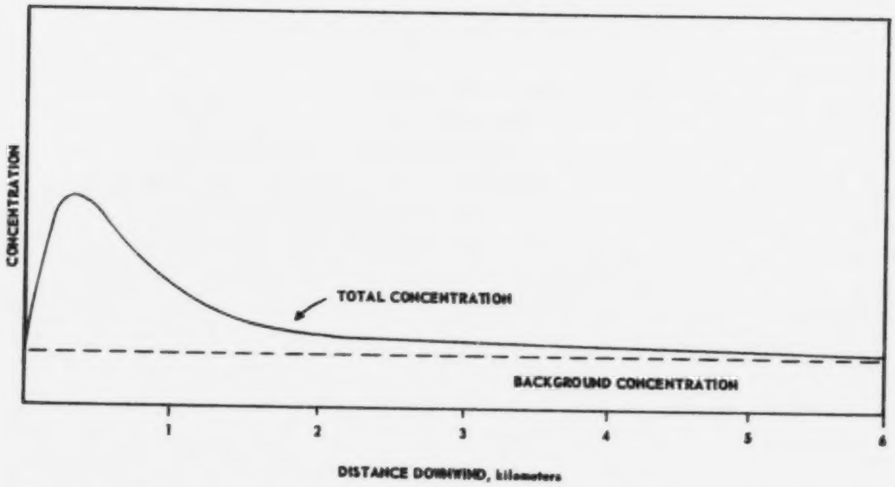

Figure 2. Variation with distance of total concentrations at surface downwind from an elevated source (schematic).

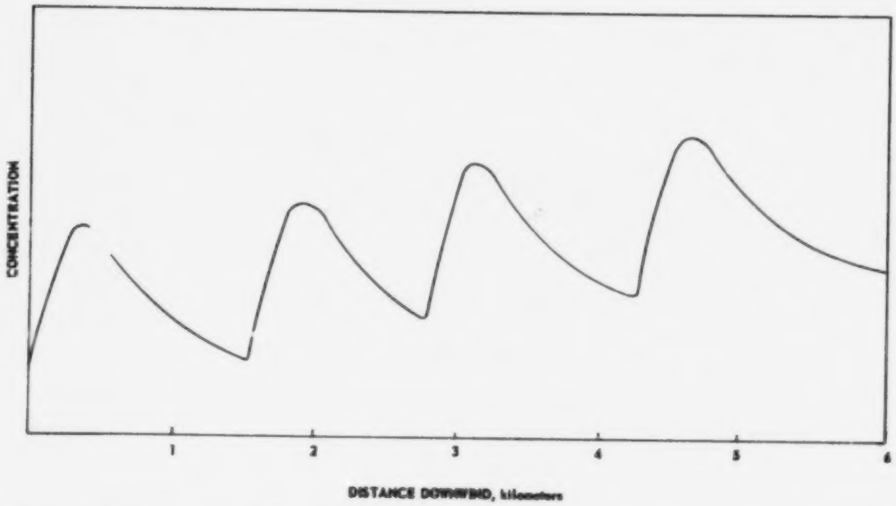

Figure 3. Variation with distance of total concentrations at surface downwind from a number of elevated sources located along a line parallel to the mean wind (schematic).

Now, if you visualize a series of such point sources all in a line along the wind you would get the conditions shown in Figure 3. The first source adds to the background concentration its typical hump, which falls off and leaves the background slightly higher, and then the next one does the same thing. Thus there is a gradual increase in the background.

In Figure 3 I have assumed schematically that all of the sources are very large, each producing a big hump and then declining in the course of over a kilometer, and that all of them are located exactly along the wind direction. This, of course, in general would not be true. If you had random sized and randomly spaced sources spread over an area, the effects along the axis would look like that shown in Figure 4. In this case one after another of the sources would contribute at random intervals and with random intensities. The background concentration goes up as a result of the successive decay of each of these sources. The plume axis of the first one source is assumed to be the line along which the concentration is computed. Occasionally, this line will strike a source which is approximately on the same plume axis, but in general the sources will be some distance from it.

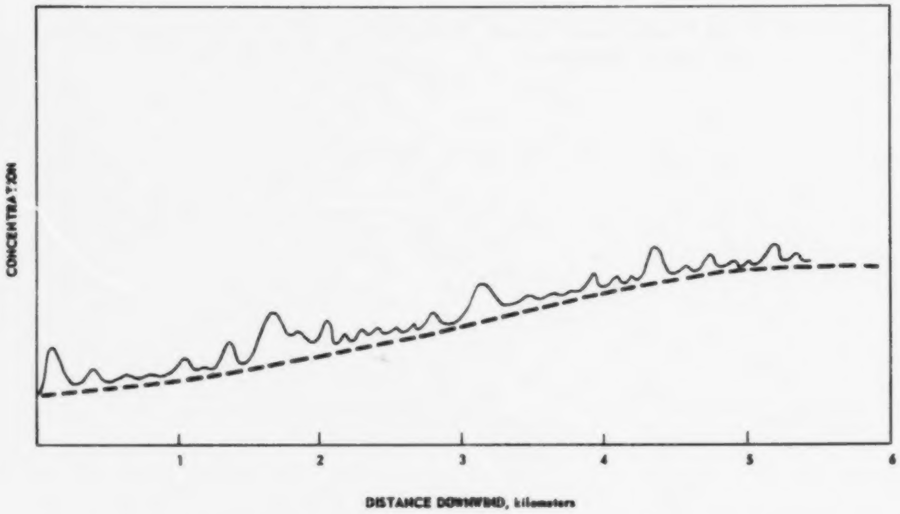

Figure 4. Variation with distance of surface concentrations from randomly sized and spaced elevated sources (schematic).

To get a quantitative estimate of the increase in background concentration due to an area source of this sort, we must express the intensity of the source in terms of a smooth function $E(x, y, t)$. The boundary conditions for the solution of the equation then would be that at the ground, i.e., at $z = 0$, F_z, the upward flux, is just equal to the source function. (For the moment we assume that the sources are all at the ground.) We further assume that at sufficiently great heights the concentration goes to zero, and at the point where the air first begins to cross the source area the concentration is zero. These boundary conditions,

$$\begin{aligned} F_z &= E\,(x,\ y,\ t) \text{ at } z = 0 \\ C &= 0 \text{ at } z = \infty \\ C &= 0 \text{ at } x = 0. \end{aligned} \qquad (3)$$

are adequate to determine a solution if A_x, A_y, and A_z are known.

In general, A_x, A_y, A_z are functions of z, because of the variation of the lapse rate with height and the variation of the size of turbulent eddies with height. They are in general also functions of x and of y, because of variations of the lapse rate in the horizontal and because of the variation in the roughness due to buildings and other irregularities of terrain.

To solve the diffusion equation under these conditions is a very difficult problem when you have to allow for the variations of all these quantities, and even then, as I mentioned, this is a simple and not a rigorous way of approaching atmospheric diffusion.

For a first crude approximation, we shall assume that A_z is constant and equal to A, and that the variation of C in the x direction, taken to be the wind direction, and the variation in the y direction are much smaller than the variation in the z direction. In that case the equation reduces to equation 4.

$$\frac{\partial C}{\partial t} = A\,\frac{\partial^2 C}{\partial z^2} \qquad (4)$$

$F_z = E$, a constant, for $x > 0$. $F_z = 0$ for $x \leq 0$.

With these boundary conditions, assuming also that E is constant and not dependant on x, y, or t, we can get an analytic expression for the solution, which is given by equation 5.

$$C = \frac{E}{\sqrt{A}} \left\{ \frac{2\sqrt{t}}{\sqrt{\pi}}\, e^{-\frac{z^2}{4At}} - \frac{z}{\sqrt{A}}\, \mathrm{erfc} \left(\frac{z}{2\sqrt{At}} \right) \right\} \qquad (5)$$

At the ground, z equals zero, the concentration reduces to the very simple expression given in equation 6. At $Z = 0$,

$$C = \frac{2\,E\sqrt{t}}{\sqrt{\pi A}} \qquad (6)$$

This equation is similar to the one that Dr. Schmidt showed yesterday.

If, furthermore, we concern ourselves with an air column which is moving across the area with a constant velocity, U, in the x direction, then t = x/U, and we have the expression shown in equations 5a and 6a.

$$C = \frac{E}{\sqrt{A}}\left\{\frac{2\sqrt{x}}{\sqrt{\pi U}}e^{-\frac{Z^2U}{4Ax}} - \frac{Z}{\sqrt{A}}\operatorname{erfc}\left(\frac{Z\sqrt{U}}{2\sqrt{Ax}}\right)\right\} \qquad (5a)$$

$$C = \frac{2E\sqrt{x}}{\sqrt{\pi AU}} \qquad (6a)$$

Equation 6 and 6a give some indication of the way that you would expect the background concentration due to an area source to change as the air moves across it. It varies with the square root of the time that the air moves along its trajectory over the source, or, if the wind is constant over the area source, then it varies as the square root of the distance along the path of the column as it moves across its source.

For a numerical example, let us assume that the average emission of hydrocarbons from automobile traffic in Los Angeles is 2 tons per square mile per day and is evenly distributed. This corresponds to a value of E of approximately 10^{-9} gram per square centimeter per second.

If the wind speed is 1 meter per second and you express the concentration in parts per million by mass, which is commonly called in meteorology the mixing ratio, the proportion by mass at various distances is shown in Table 1. The concentration is

TABLE 1

HYDROCARBON CONCENTRATIONS (ppm by mass)
AT WINDSPEED OF 1 METER PER SECOND

Eddy Diffusivity (A)	Distance Downwind, km						
	0.1	0.9	2.5	6.4	10.0	20.0	40.0
$5\cdot 10^2$	0.41	1.2	2.0	3.2	4.1	4.9	8.0
10^3	0.29	0.86	1.4	2.3	2.9	3.4	5.7
$5\cdot 10^3$	0.13	0.38	0.64	1.0	1.3	1.5	2.5
10^4	0.09	0.27	0.45	0.72	0.91	1.1	1.8
$5\cdot 10^4$	0.04	0.12	0.20	0.32	0.41	0.49	0.80

expressed in parts per million, for various values of A given in the first column. The distances downwind from the start of the source area are given in kilometers.

Values of A are really not well known, but in a general way the values near the top of the table correspond to fairly strong inversions, or moderate inversions, and values near the bottom correspond to lapse conditions.

Taking any one value of A, it is seen that the concentration increases downwind as the air passes the sources, as would be expected. On the assumptions made, this variation is exactly as the square root of the distance, so that the rate of increase of concentration tapers off as the air passes over more and more of the source area.

Looking now at the effect of the various coefficients of diffusion, we see that the concentration is greatest for the slowest diffusion, corresponding to the inversion, and is least for the greatest diffusivity, corresponding to a relatively large lapse condition.

The computation thus gives a clear indication of the factors controlling the concentrations of pollutants, namely source intensity, windspeed, and the intensity of turbulence, represented by the A, which in turn is controlled by roughness of terrain, atmosheric stability, windspeed, and windshear.

I have presented this discussion not as an answer to the diffusion problems but rather to focus attention on the elements that need investigation.

As long ago as 15 years, when I was first consulted on the air pollution problem, I pointed out the urgent need for a census of pollution sources to give their locations and intensity. The Air Pollution Control District of Los Angeles County has carried out such censuses to some extent.

Figure 5 shows a map made some years ago of pollution sources over the Los Angeles basin, as an indication of the type of data that are needed. The chemical and process industries are very dense in the section called Vernon, southeast of central Los Angeles, and are sparse in residential areas.

Some of the municipal incinerators shown on the map have actually been closed down because they didn't meet the rules of the Air Pollution Control District. This map is based on data from 1952 for the most part.

The isopleths of traffic density also will have changed considerably from the 1951-52 data represented here. The lines are

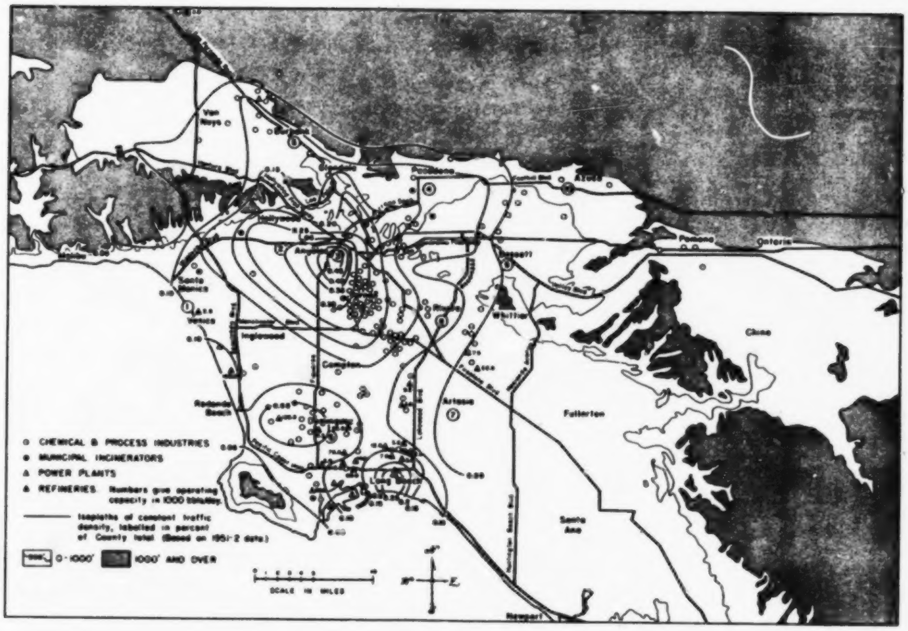
Van Nuys
Pasadena
Azusa
Pomona
Ontario
Santa Monica
Venice
Inglewood
Compton
Redondo Beach
Whittier
Artesia
Long Beach
Fullerton
Santa Ana
Chino
Newport
CHEMICAL & PROCESS INDUSTRIES
MUNICIPAL INCINERATORS
POWER PLANTS
REFINERIES. Numbers give operating capacity in 1000 bbls/day.
Isopleths of constant traffic density, labelled in percent of County total (Based on 1951-2 data)
0-1000'
1000' AND OVER
SCALE IN MILES
N
E

Figure 5. Map of traffic density and industrial sources of pollution in Los Angeles County.

labelled in terms of the percentage of the county total per square mile. The one labelled 0. 1, for instance, has one-tenth of a percent of the county total per square mile. In central Los Angeles it reaches as much as 45/100ths of a percent per square mile. If one takes this fraction per square mile, multiplies it by the total amount of gasoline consumed in Los Angeles County in a day, and then by the fraction that comes out in the exhaust unburned or partially burned, one can get the amount of hydrocarbons lost from automobile exhausts per square mile. So we have a pattern of isopleths which can be interpreted as the emission function, E, as a function of x and y, expressed in terms of tons per square mile, or whatever unit you choose.

If, corresponding to each of these circles and triangles, we had similar information about the source strength for each particular pollutant, we could draw isopleths for them also and have a function E for other pollutants, for example SO_2, or whatever other pollutants one is interested in. This is the kind of map that I feel is required to come from censuses of the amount of pollution put into the atmosphere. This map was prepared on a whole-day basis, but since traffic varies with time of day hourly maps of this sort should be plotted also.

To evaluate the trajectory of the air as it crosses the source area, it is necessary to know not only how the emission intensity varies over an urban area but also how the wind varies over time and space. Figures 6 - 10 represent the flow pattern over Los Angeles during a particular 24-hour period in 1954, starting at the time of the maximum sea breeze, 2:30 p. m., September 21, and ending at the same time September 22.

In Figure 6, you see that the air is streaming across the basin from the coast to the mountains at the time of maximum sea breeze. The solid lines with arrows are streamlines and the dashed lines are isotachs, or velocity lines in miles per hour. At the coast the speed is 16 miles per hour, but farther inland it drops off to 8 miles per hour.

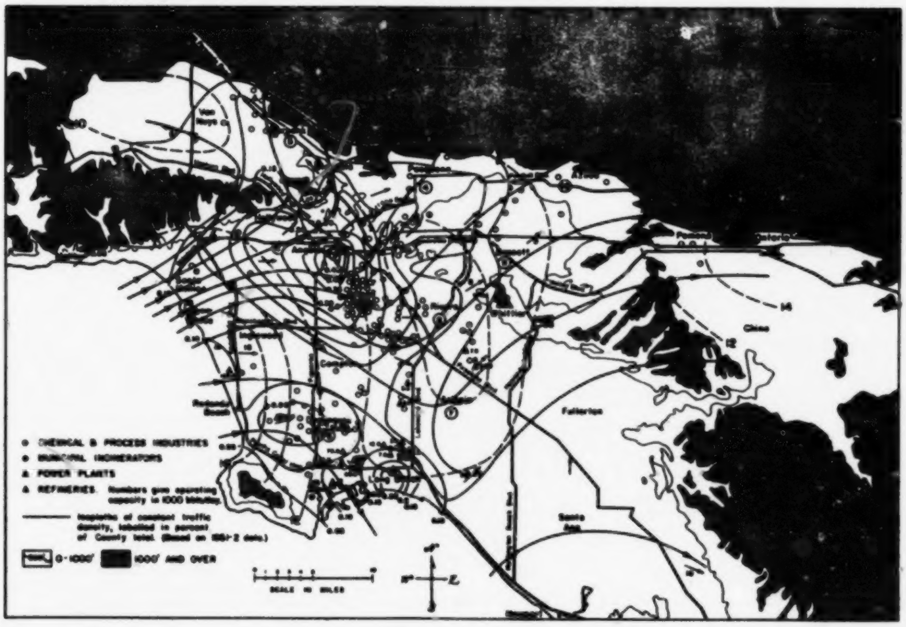

Figure 6. **Streamlines (solid lines) and isotachs (lines of equal speed, dashed lines) for 1430 PST September 21, 1954. Speeds are given in miles per hour beside station arrows and at ends of isotachs.**

Figure 7 shows the pattern 8 hours later. By 10:30 p. m. the land breeze has already sprung up, the air is flowing out from the mountains and across the coast, with speeds of less than 4 miles per hour over most of the basin, and there is even a line, enclosing an area for which the winds are less than 2 miles per hour. Thus the winds have become very light and from the land on the whole.

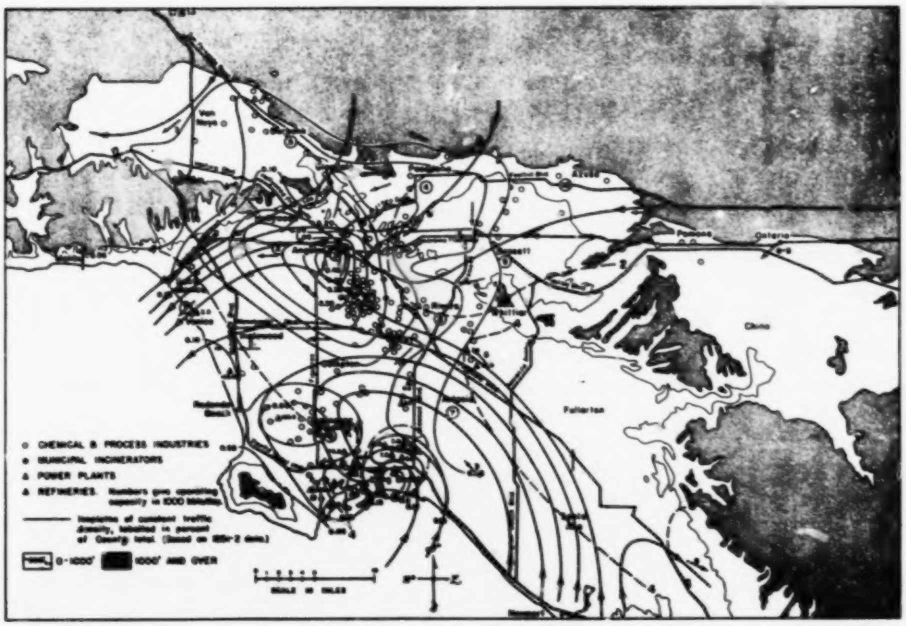

Figure 7. Streamlines (solid lines) and isotachs (lines of equal speed, dashed lines) for 2230 PST September 21, 1954. Speeds are given in miles per hour beside station arrows and at ends of isotachs.

Figure 8, for 6:30 a. m. shows the land breeze at roughly its maximum, with a 6-mile-an-hour wind right at the coast, but over most of the area the winds are 2 miles an hour or less, very light winds carrying the air back from the inland area toward the coast and then off-shore.

At 10:30 a. m., Figure 9, the seabreeze has already started. One interesting thing, at 2:30 p. m. September 21 the seabreeze was all coming from the west coast of the basin, but during the early part of the seabreeze there is a line of convergence, with part of the seabreeze coming from the south coast. At 10:30 the speeds range from 4 to 10 miles per hour, rather less than at 2:30 p. m. Figure 10 shows the situation at 2:30 p. m. September 22, when the seabreeze is again near its maximum.

This series of charts shows how in a complicated topography, with light winds such as we have in Los Angeles in the warm half of year, there is quite a variation of winds with distance inland. In computing diffusion in such terrain one cannot assume a wind in a uniform direction with constant speed.

Figure 11 shows a trajectory computed from hourly maps such as the ones in the preceding figures. This one is the trajectory reaching Pasadena at noon on the 23rd of September, 1954.

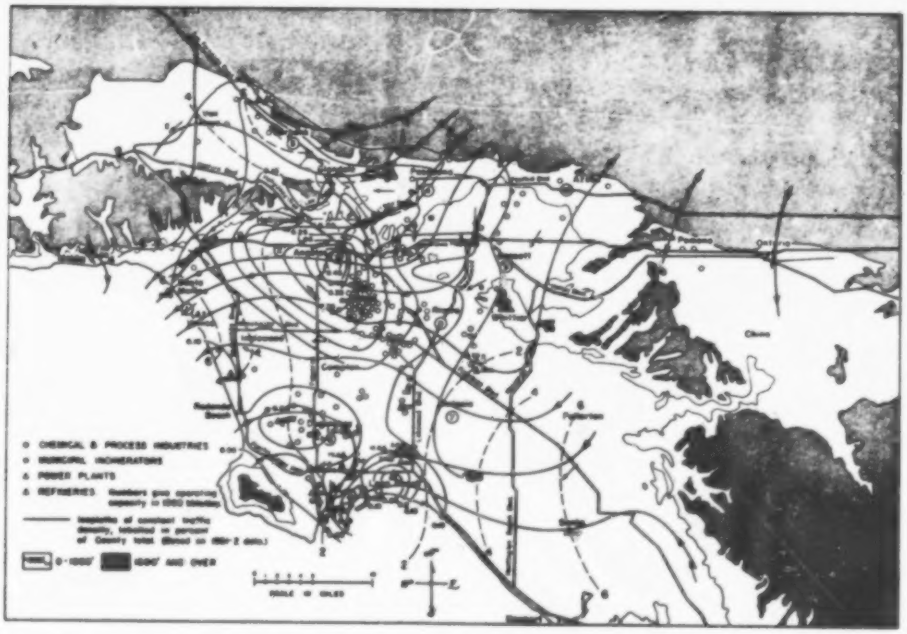
Pomona
Ontario
Chino
Fullerton
SCALE IN MILES

Figure 8. Streamlines (solid lines) and isotachs (lines of equal speed, dashed lines) for 0630 PST September 22, 1954. Speeds are given in miles per hour beside station arrows and at ends of isotachs.

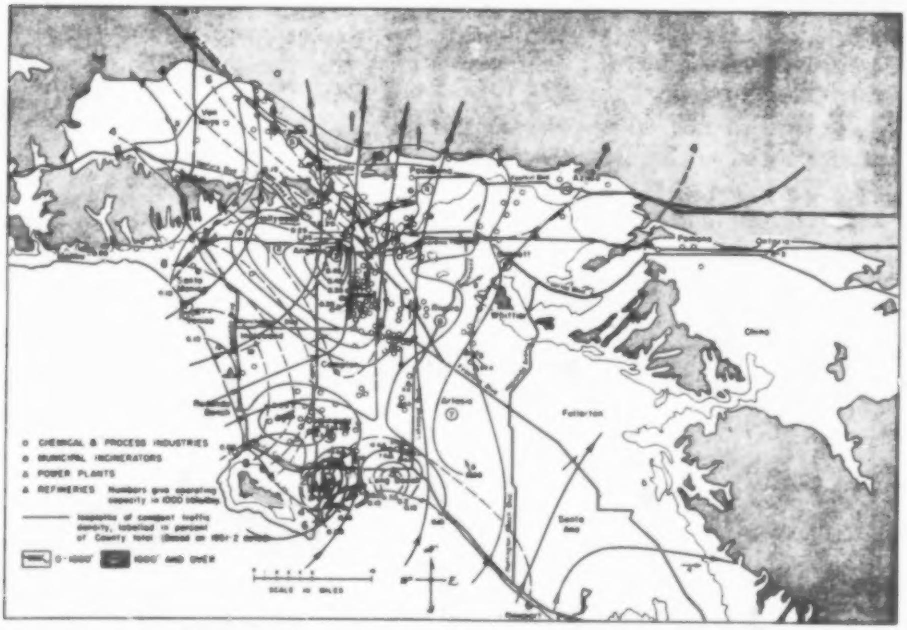
Pomona
Ontario
Chino
Whittier
Fullerton
Santa Ana
CHEMICAL & PROCESS INDUSTRIES
MUNICIPAL INCINERATORS
POWER PLANTS
REFINERIES
SCALE IN MILES

Figure 9. Streamlines (solid lines) and isotachs (lines of equal speed, dashed lines) for 1030 PST September 22, 1954. Speeds are given in miles per hour beside station arrows and at ends of isotachs.

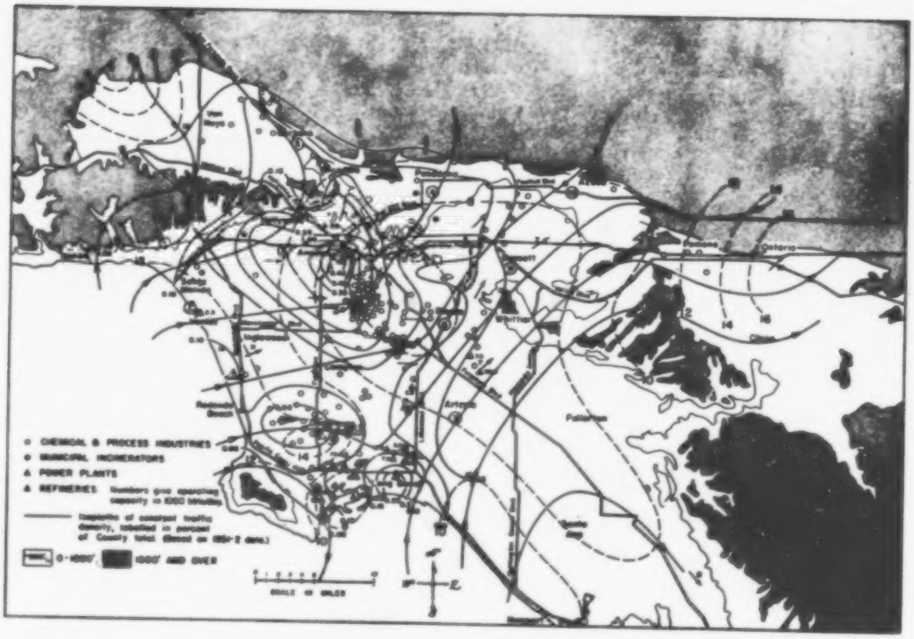

Figure 10. Streamlines (solid lines) and isotachs (lines of equal speed) dashed lines) for 1430 PST September 22, 1954. Speeds are given in miles per hour beside station arrows and at ends of isotachs.

The large circle is Pasadena, and the smaller circles show the positions of the air at the hours given by the numbers beside them. The air went in across the coast with the beginning of the seabreeze on September 22, streamed inland, reached a point not far from Pasadena that evening, meandered southwestward slowly during the night, started northeastward again with the beginning of the seabreeze the next day and reached Pasadena 23 hours after it left the coast. A little later the results of a computation of the variation of hydrocarbons and carbon monoxides along this trajectory will be presented. To evaluate the concentrations along the trajectory we should know, in addition to these windflow patterns, the variation of coefficient diffusivity, A, in the horizontal and in the vertical.

Figure 12 shows a temperature sounding typical of the warm half of the year near the coast in Los Angeles. This is on a rotated tephigram, so that the constant temperature lines (labelled in °C) slope upward to the right and the dry adiabatic or constant potential temperature lines (labelled in °K) slope upward to the left. The numbers on the left of the sounding curve are heights in meters, on the right water vapor mixing ratio in parts per thousand. The temperature decreases with height for the first

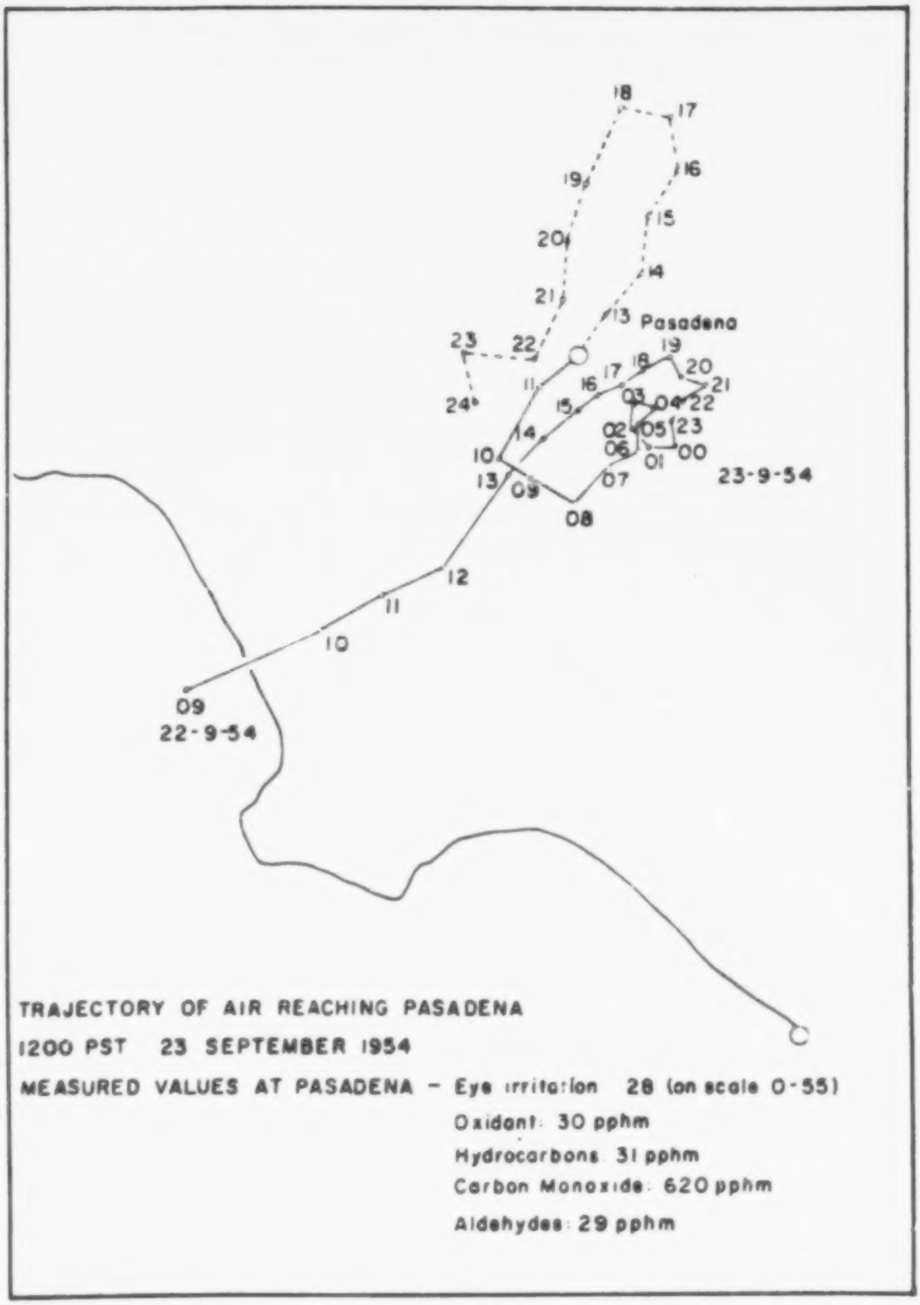
18
17
19
16
15
20
21
14
13
Pasadena
23
22
19
20
18
17
21
16
11
15
03
04
22
24
02
05
23
14
06
10
00
01
13
07
23-9-54
09
08
12
11
10
09
22-9-54
TRAJECTORY OF AIR REACHING PASADENA
1200 PST 23 SEPTEMBER 1954
MEASURED VALUES AT PASADENA – Eye irritation 28 (on scale 0-55)
Oxidant: 30 pphm
Hydrocarbons: 31 pphm
Carbon Monoxide: 620 pphm
Aldehydes: 29 pphm

Figure 11. Trajectory of air arriving at Pasadena at noon September 23, 1954 with high values of oxidant and eye irritation.

few hundred meters are practically at the adiabatic rate, and then there is an inversion of temperature of a considerable thickness, above which the temperature decreases again.

Thus, instead of a constant value of A, corresponding to some particular lapse rate, it varies with height. For the computation that I will show, which is an unrealistic one also, I have assumed that A is practically infinite for the layer of adiabatic lapse rate, and extremely small beginning where the inversion starts. The whole computation is intended to be schematic.

Figure 12 shows a typical sounding near the coast, but actually even there it varies with time of day, and as the air moves inland during the day there is variation with position. For an accurate computation, then, one should account for the variation of A not only with height, but also with time and with distance

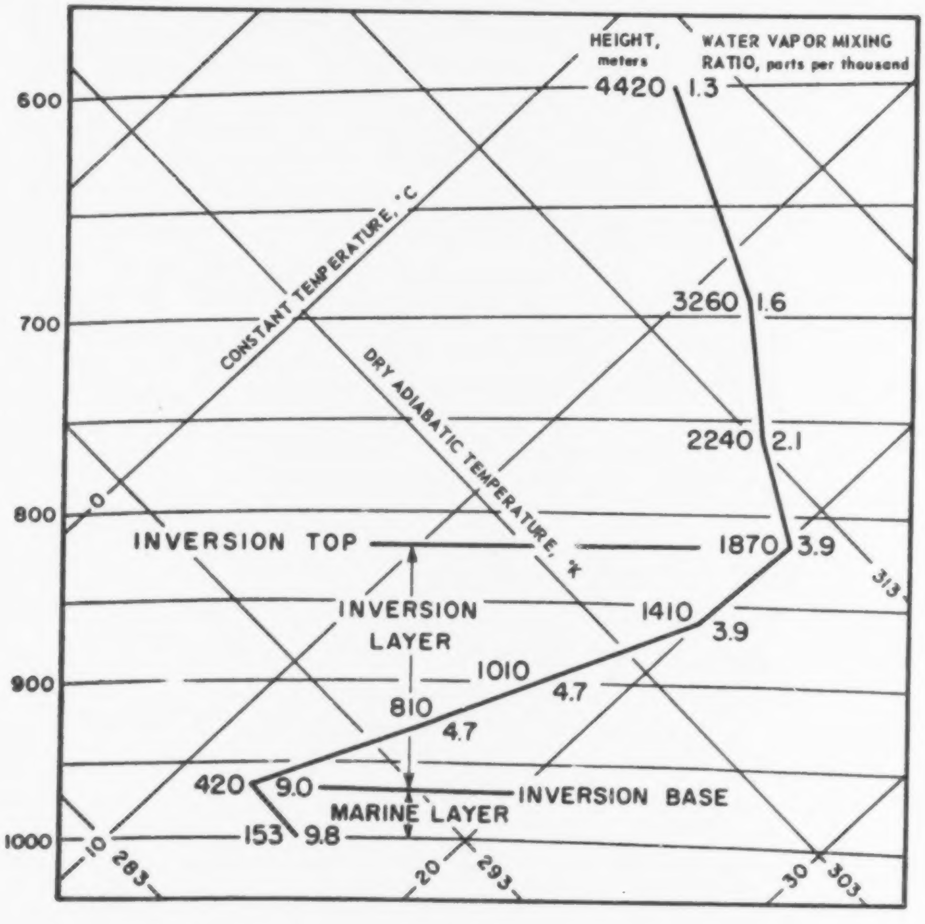

Figure 12. Typical sounding at southern California coast in summer.

in the horizontal. Rigorous account of all these factors would be too difficult to carry out analytically, but might be attempted by high-speed electronic digital computers, or perhaps as the next paper will discuss, by analog computers.

The results of the computation of the hydrocarbon and carbon monoxide concentrations for the trajectory that we saw in Figure 11, using the distribution of E corresponding to the traffic density pattern shown in 1952, Figure 5, are shown in Figure 13. We assume a parcel of air starting at the coast containing no hydrocarbons and no carbon monoxide, and compute the amount that is added due to the traffic density as it follows the trajectory shown in Figure 11. For each segment of the trajectory the source strength is assumed proportional to the corresponding traffic density line, and the diffusion into the air parcel below the inversion is computed. The computed hydrocarbon value for the point where the trajectory reaches Pasadena at noon on the 23rd is about 20 pphm, the observed value measured was 31 parts per hundred million, so that the computation gives a value of the same general magnitude, although not very close.

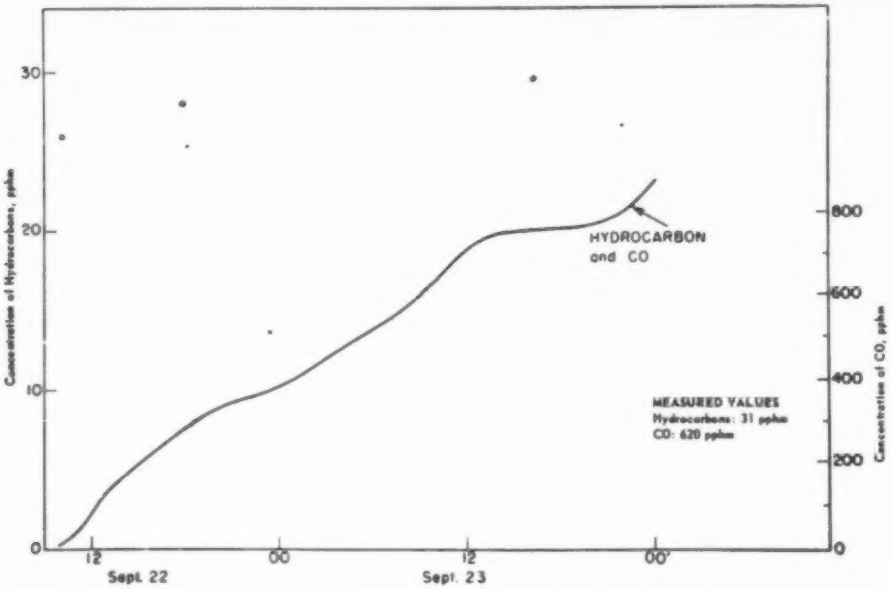

Figure 13. Estimated accumulation of hydrocarbons and carbon monoxide from motor traffic along trajectory of Figure 11.

For the carbon monoxide, the computed value is about 700, and the measured value was 620. Thus even with the very crude method of evaluation the computation comes not very far from the measured values, on the assumption that the measured values are due to the addition of the hydrocarbons and carbon monoxide from automobile traffic without any other sources and without any destruction of these contaminants. Actually, we know that there are other sources, and there may also have been a background value at the start, since the air may have moved out from the land to sea the previous day and then moved in again. Thus there are ways of explaining the fact that the hydrocarbons are too low on this basis. Similarly, the fact that the computed value of the carbon monoxide is too high can be explained, since presumably some of the carbon monoxide was oxidized during the passage across the basin. But also, of course, there are many other deficiencies in the computations and one should not take the correspondence too seriously.

Even this crude theory gives some promise that if the wind and temperature conditions are forecast accurately and if we have some way of deriving from them the values of A, we could make fair forecasts of the concentrations of pollutants for which the area emission strength is known. As theory improves and data for verification become available, the accuracy of forecasts of concentration will improve correspondingly.

The principle of area emission intensities as opposed to individual source strengths applies not only to the forecasting problem, but also to the problem of zoning urban areas with respect to industrial developments and traffic patterns. The criterion should be to limit the increases in sources to the maximum area emission intensity that will not produce undesirable concentrations. This intensity for an area may be produced by individual large sources or by many small ones.

The zoning restrictions should recognize this fact. To arrive at a criterion for the acceptable area emission intensity, as for accurate forecasting, it is necessary to know much more about the process of diffusion over urban areas. Recognizing that the approach through statistical studies of turbulent diffusion may turn out to be the best way to get the answer, we may still couch the question in the terms of the exchange coefficient A. The question then would be how is A affected by the terrain of complex urban areas, which consist of tall and low buildings, trees, hills, heat sources from residences and industrial processes, and moving vehicles. How does it vary with the wind, especially for low average wind speeds, in which condition the fluctuations have as large magnitude as the average? How does it vary with lapse rate and how does it vary with height under all these circumstances? When the variation of A is known or the equivalent clarification of the turbulent diffusion process is obtained by other means, it will be necessary to apply it to the distribution of E for each urban community under models typical of adverse weather conditions to estimate the resulting concentrations of pollutants. The integration of the diffusion equation or its equivalent will probably be too difficult to carry out analytically, as I have already mentioned. High-speed computers will have to be used. But when we have adequate theory and computing techniques and the knowledge of the area emission functions it will be possible to compute the effects of prolonged adverse weather conditions not yet experienced or the effect of changing the emission distribution by the addition of new sources or the development of new commercial, industrial, and residential areas.

Analog Computing Techniques Applied to Atmospheric Diffusion: Continuous Area Source*

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Summary

An electronic analog computer has been used to obtain solutions to the diffusion equation. The model is that of a continuous area source located on the ground in steady-state conditions. The crosswind-integrated concentration is obtained as a continuous function of distance downwind for discrete height intervals. The versatility of analog simulation is demonstrated by introducing a variety of boundary conditions and other parameters into the basic model. With this approach the effects of an inversion, radioactive decay, gravitational settling, ground reflection, ground absorption, etc. are conveniently included. Windspeed and eddy diffusivity can be arbitrarily varied with height. Analog simulation may be extended to treat the problem of photochemical reactions that occur during the diffusion process.

The purpose of this paper is to show how the electronic analog computer may be used to simulate atmospheric diffusion. The example chosen to illustrate this technique is that of diffusion of particulate matter from an area source on the ground in steady-state conditions. No specific physical problem is envisioned here but, as the solutions are obtained in nondimensional parameters, they could apply to a wide variety of situations. For example they could be applied to the diffusion of industrial effluents from a group of stacks, of automobile exhaust fumes from a city, or, at the other end of the scale, of pollen from a cluster of plants. The only restriction on scale is one implied by the choice of a wind profile, a power law in this case.

In this problem the coordinate axes are oriented with the x-axis downwind, the y-axis crosswind, and the z-axis vertical. The source, as shown in Figure 1, is circular and centered at the point (a/2 . 0 . 0). The mean wind vector is assumed to have no components in the y or z directions. The source strength is assumed to be constant over the source area.

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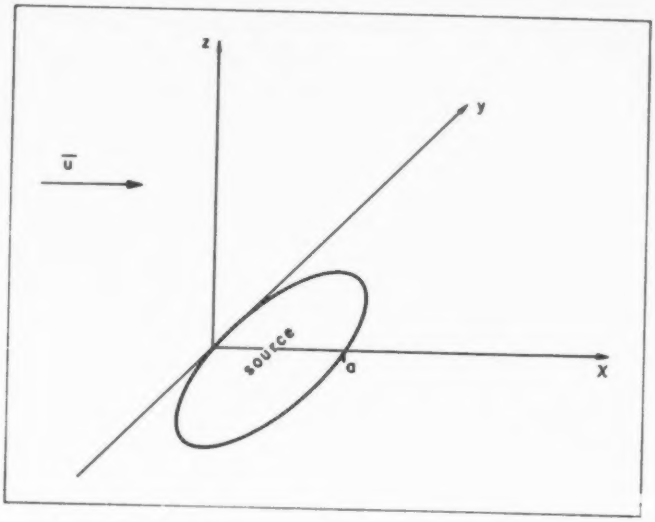

Figure 1. Orientation of the coordinate axis relative to the source and to the mean wind direction. The center of the circular source is located at the point (a/2, 0, 0) in the x, y, z space.

THE MATHEMATICAL-PHYSICAL MODEL

The diffusion equation as used here may be stated as

$$\bar{u}(z)\ \frac{\partial \chi}{\partial x} = \frac{\partial}{\partial z}\left[K(z)\ \frac{\partial \chi}{\partial z}\right] + \frac{\partial}{\partial y}\left[K(y)\ \frac{\partial \chi}{\partial y}\right] + f\ \frac{\partial \chi}{\partial z} - \lambda \chi \quad (1)$$

with the following boundary conditions:

$$\chi \rightarrow 0 \quad \text{as} \quad x \rightarrow 0 \ \text{ for all } y,\ z$$
$$\text{and} \quad x,\ |y|\ ,\ z \rightarrow \infty$$

$$\lim_{z \rightarrow 0} \left[K(z)\frac{\partial \chi}{\partial z} + f\chi\right] = -Q + p \lim_{z \rightarrow 0} \chi$$

where

χ = concentration
$\bar{u}$ = mean wind speed in the x-direction
K = eddy diffusivity
f = fall speed of the particulate
λ = decay rate, e. g. radioactive decay

in consistent units.

The source strength is a constant Q over the region defined by the relation

$$y^2 + (x - a/2)^2 = a^2/4;\ z = 0.$$

The rate of loss of material to the ground is assumed to be proportional to the "local" concentration near the ground with the proportionality constant p. The statement of the boundary condition at the ground was adopted from the work of Calder.[1]

If the mean wind speed and eddy diffusivity profiles are given by

$$\bar{u}(z) = \bar{u}_1 \left[\frac{z}{z_1}\right]^{1/7}, \quad K(z) = K_1 \left[\frac{z}{z_1}\right]^{6/7},$$

then equation (1) may be written in nondimensional form as follows:

$$\frac{1}{C}\frac{\partial S}{\partial X} = Z^{-1/7} \frac{\partial}{\partial Z}\left[Z^{6/7} \frac{\partial S}{\partial Z}\right] + F Z^{-1/7} \frac{\partial S}{\partial Z} - D Z^{-1/7} S \qquad (2)$$

where S is the nondimensional crosswind-integrated concentration defined as

$$S = \frac{1}{\chi_o} \int_{-\infty}^{\infty} \chi dy.$$

The constant χ_o will be defined later. The other nondimensional parameters are

$$X = \frac{K_1}{C \bar{u}_1 z_o^2} \left[\frac{z_o}{z_1}\right]^{5/7} x$$

$$Z = \frac{1}{z_o} z$$

$$F = \frac{z_o}{K_1} \left[\frac{z_o}{z_1}\right]^{-6/7} f$$

$$P = \frac{z_o}{K_1} \left[\frac{z_o}{z_1}\right]^{-6/7} p$$

$$D = \frac{z_o^2}{K_1} \left[\frac{z_o}{z_1}\right]^{-6/7} \lambda$$

The boundary conditions for equation (2) are

$$S \to 0 \quad \text{as } X \to 0 \text{ for all } Z$$
$$\text{and as } X, Z \to \infty$$

$$\lim_{z \to 0} \left[Z^{6/7} \frac{\partial S}{\partial Z} + (F - P) S\right] = -B \sqrt{AX - X^2} \left[1 - h(X - A)\right]$$

where

$$\chi_o = \frac{2\,C\,Q\,\bar{u}_1\,z_o^3}{B\,K_1^2}\left[\frac{z_o}{z_1}\right]^{-11/7}$$

All of the constants involved can be grouped into two types. The first type, scale parameters, includes $\bar{u}_1$, K_1, z_1, and z_o. These determine the conversion from nondimensional units to physical units and, therefore, the scale of the problem. The second type may be called convenience parameters and have no physical significance. These parameters, B and C, are used solely to scale the problem on the analog computer.

PREPARATION FOR ANALOG COMPUTATION

Equation (2) is stated in terms of two independent variables, X and Z. Since the analog computer can integrate with respect to only one independent variable, one of them, Z, must be replaced with finite differences. Computer time is used to represent X. Implementation of finite differences requires a new model, which is shown in Figure 2. The atmosphere is divided into 10 layers in the vertical, and the thickness of the layer increases exponentially with height. Each layer incorporates the properties of the atmosphere that it replaces. For convenience, the layers are labeled 1 through 10. Thus the notation $S_n(X)$ represents the crosswind-integrated concentration in the nth layer as a function of distance downwind.

The general finite difference expression for stations 1 through 9 is

$$\begin{aligned}\frac{1}{C}\frac{dS}{dX}\bigg|_n = {} & \frac{Z(n)^{-1/7}}{\Delta\ Z(n)}\left[\frac{Z(n+1/2)^{6/7}}{\Delta\ Z(n+1/2)}\left(S_{n+1}-S_n\right)\right. \\ & \left. - \frac{Z(n-1/2)^{6/7}}{\Delta\ Z(n-1/2)}\left(S_n - S_{n-1}\right)\right] \\ & + \frac{F\ Z(n)^{-1/7}}{2\,\Delta\ Z(n)}\left(S_{n+1}-S_{n-1}\right) \\ & - D\ Z(n)^{-1/7} S_n . \qquad (3)\end{aligned}$$

The expression for station 1, which is next to the ground, is different because of the boundary conditions that must be inserted. The boundary condition in finite difference form is

$$\frac{Z(1)^{6/7}}{\Delta Z(1)} (S_1 - S_o) + (F - P) S_o = -B\sqrt{|AX - X^2|}. \tag{4}$$

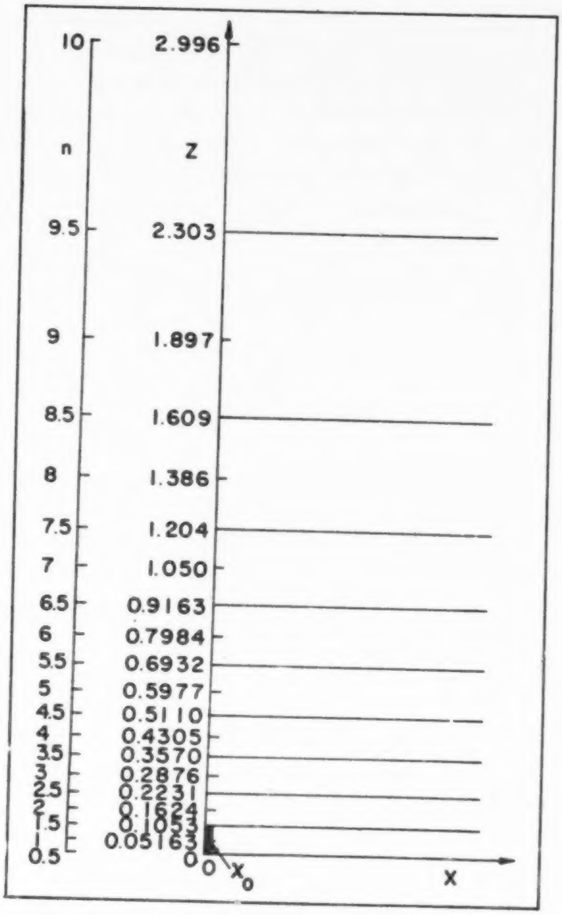
10
2.996
n
Z
9.5
2.303
9
1.897
8.5
1.609
8
1.386
7.5
1.204
7
1.050
6.5
0.9163
6
0.7984
5.5
0.6932
5
0.5977
4.5
0.5110
4
0.4305
3.5
0.3570
3
0.2876
2.5
0.2231
2
0.1624
1.5
0.1053
1
0.05163
0.5
0
0
X0
X

Figure 2. Finite difference model showing the vertical coordinate axis relations.

From this, an expression can be found for S_o, which is a virtual station below ground. The meaning of this is that in the finite difference model, a virtual station below ground is given a concentration such that the boundary condition for flux at the ground is satisfied. The boundary condition at $Z \to \infty$ is satisfied by setting $S_{10} = 0$ which is at infinity due to the exponential cell spacing.

ANALOG MODEL

The physical model now consists of a stack of planes spaced exponentially in the z direction. It is supposed that each plane has a capacity for containing some of the diffusing substance just equal to that of the layer of atmosphere that it replaces. At a given point in x, a traverse in the z direction shows the properties of the atmosphere lumped at discrete intervals. This model can be simulated with an electric analog, where each of the circuit components is analogous to some property of the atmosphere. A segment of such a circuit is shown in Figure 3. The analogies shown were developed from the similarity of the node differential equations for a simple case,

$$C_n \frac{dV}{dt}\bigg|_n = \frac{1}{R_n}\left(V_{n+1} - 2V_n + V_{n-1}\right)$$

$$(\Delta z)_n \, \bar{u} \frac{d\chi}{dx}\bigg|_n = \frac{K}{(\Delta z)_n}\left(\chi_{n+1} - 2\chi_n + \chi_{n-1}\right).$$

To perform the simulation, set the resistor R_n proportional to $\Delta z/k$, the capacitor C_n proportional to $\Delta z\, \bar{u}$, and voltage V proportional to concentration. The problem time t will represent distance downstream. All these relations are stated as proportionalities so that scale factors can be used to provide reasonable

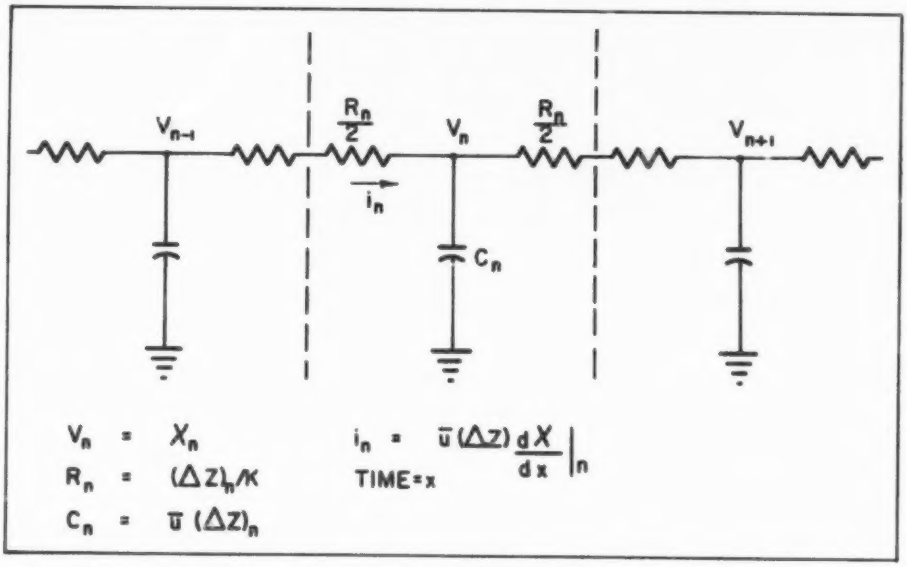

Figure 3. Typical station in the passive network analog showing the analogy between circuit components and the physical properties of the atmosphere pertinent to the diffusion problem.

values of resistance and capacitance. In general, one may relate electrical resistance to atmospheric resistance to diffusion, and electrical capacitance to the capacity of a layer of the atmosphere to hold the diffusing substance. The complete network analog is shown in Figure 4, along with the electronic analog and a representation of the physical model.

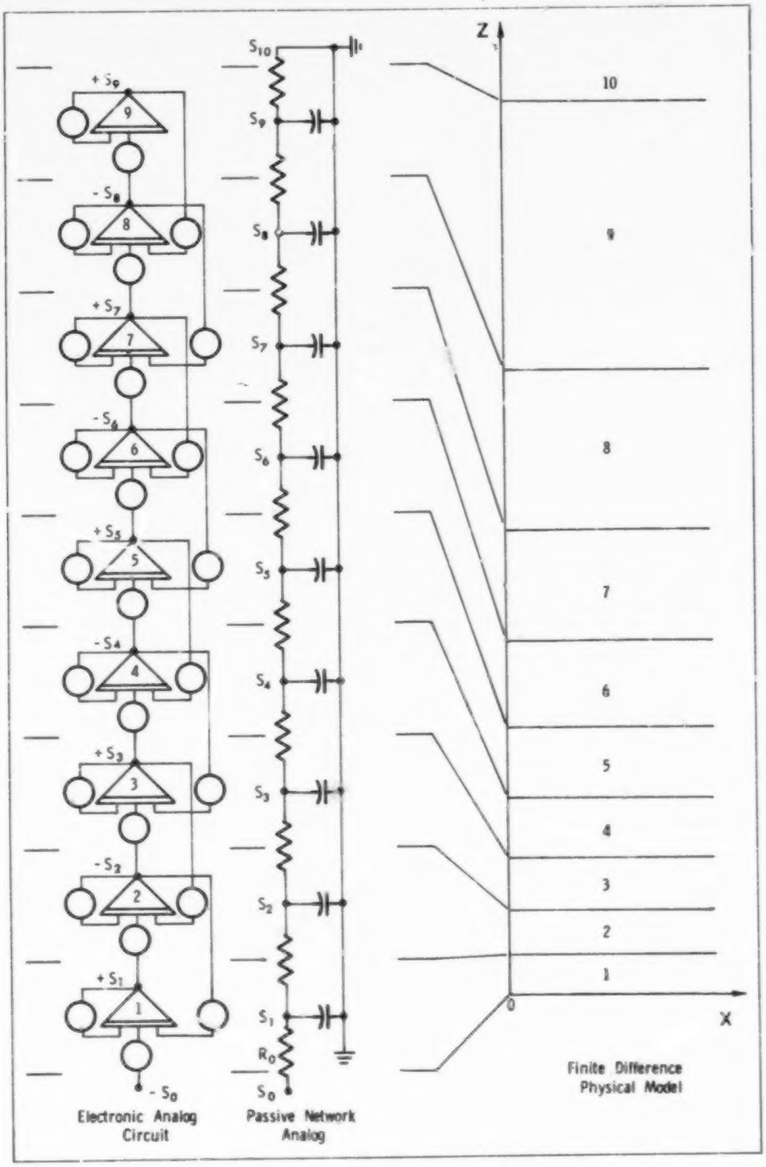
S_{10}
$+S_9$
S_9
9
10
$-S_8$
8
S_8
9
$+S_7$
7
S_7
$-S_6$
6
S_6
8
$+S_5$
5
S_5
7
$-S_4$
4
S_4
6
$+S_3$
3
S_3
5
4
$-S_2$
2
S_2
3
2
$+S_1$
1
S_1
1
Z
0
X
R_0
$-S_0$
S_0
Electronic Analog Circuit
Passive Network Analog
Finite Difference Physical Model

Figure 4. Electronic analog, passive network analog, and physical, finite difference model of the atmosphere. Note that each group of components represents a layer of the atmosphere.

The passive-circuit analog was not used in this study, but it is helpful to construct it on paper because of the insight it provides. This is particularly useful in determining the method of applying the boundary conditions.

The electronic analog circuit could be designed directly from the passive network or from the set of simultaneous differential equations. The latter method is much the easier course after the equations are reduced to the form

$$\left.\frac{dS}{dX}\right|_n = a_n S_{n+1} - b_n S_n + c_n S_{n-1}.$$

The principal element in the electronic analog is the integrating amplifier, which can be used to represent one station as shown in Figure 5. In the passive-network analog, there was a direct

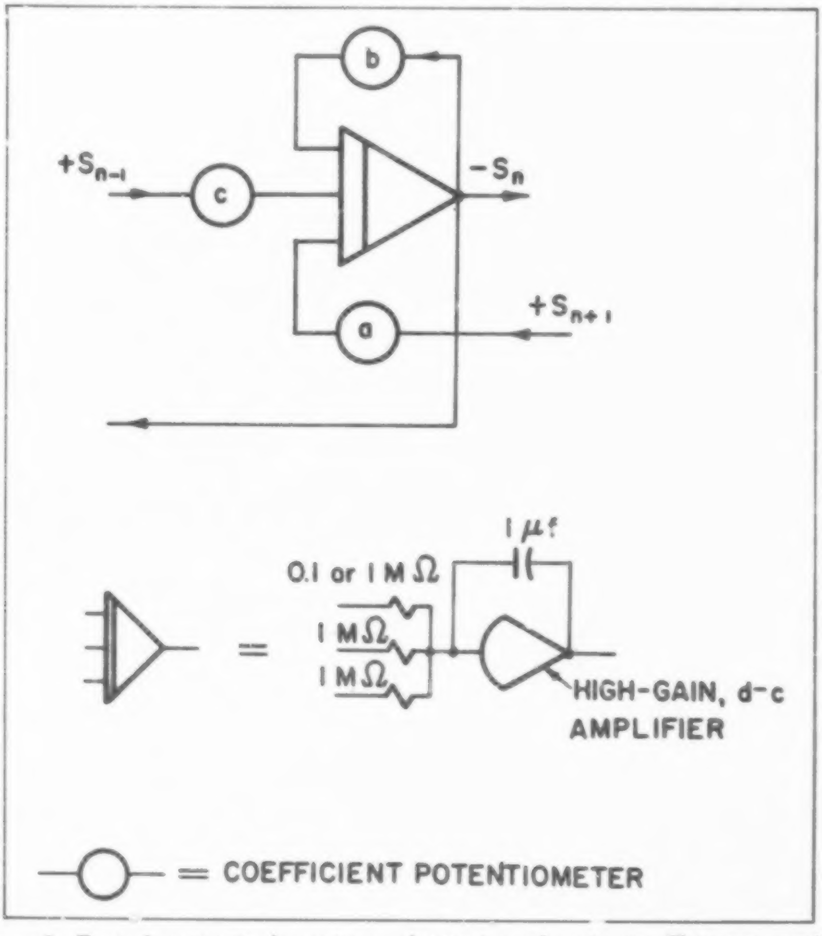

Figure 5. Typical station in the active or electronic analog circuit. The concentration is represented as a voltage, and equation coefficients as potentiometer settings.

correspondence between the circuit elements and the physical problem, while in the electronic analog, there exists a one-to-one correspondence between the circuit elements and the defining equation. The coefficients a, b, and c are set on the correspondingly designated coefficient potentiometers. The integrating amplifier sums the three inputs, integrates the sum, and inverts the sign. Ordinarily, the gain of the integrating amplifier is unity, set by the 1-megohm input resistor and 1-microfarad feedback capacitor. If one of the coefficients is greater than unity, the corresponding input resistor used is 0.1 megohm, which provides a gain of 10. This is necessary because the maximum setting of the coefficient potentiometers is 1.

The electronic circuit is much more flexible than the passive network, permitting almost any conceivable form of boundary conditions to be set up readily. In this case, a voltage is generated and fed into the network at S_o such that equation (4) is satisfied.

The accuracy of the solutions obtained with this method can be demonstrated by analogy. When the problem is set up on a computer, it is a physical system that is designed to behave like the atmosphere with respect to diffusion. This same model has been tested previously.[2] With a different input arrangement it simulated diffusion from an infinite line source. The solutions obtained were compared with available analytical solutions[3] where the errors were found to be less than 5 percent.

RESULTS OF COMPUTATION

In Figures 6 through 10 the solutions have been plotted as lines of constant, crosswind-integrated concentration for cases I through V, respectively. The following table shows what effects were used in each case.

TABLE 1

LIST OF SOLUTIONS OBTAINED AND THE VALUES OF THE PARAMETERS FOR TIME DECAY D, GRAVITATIONAL SETTLING F, GROUND SINK EFFECT P, AND THE PRESENCE OF AN INVERSION I

	Solution				
Parameter	I	II	III	IV	V
D	0	0	0	0	2
F	0	0	0	2	0
P	0	0	2	2	0
I	NO	YES	NO	NO	NO

A typical set of values will give an idea of the magnitude of these parameters. If we choose $z_0 = z_1 = 10^4$ cm, $K_1 = 10^5$ cm^2/sec, the other parameters become

$$f = 20 \text{ cm/sec}$$
$$\lambda = 0.002 \text{ sec}^{-1}$$

To express λ in terms of half-life, this becomes about 6 hours.

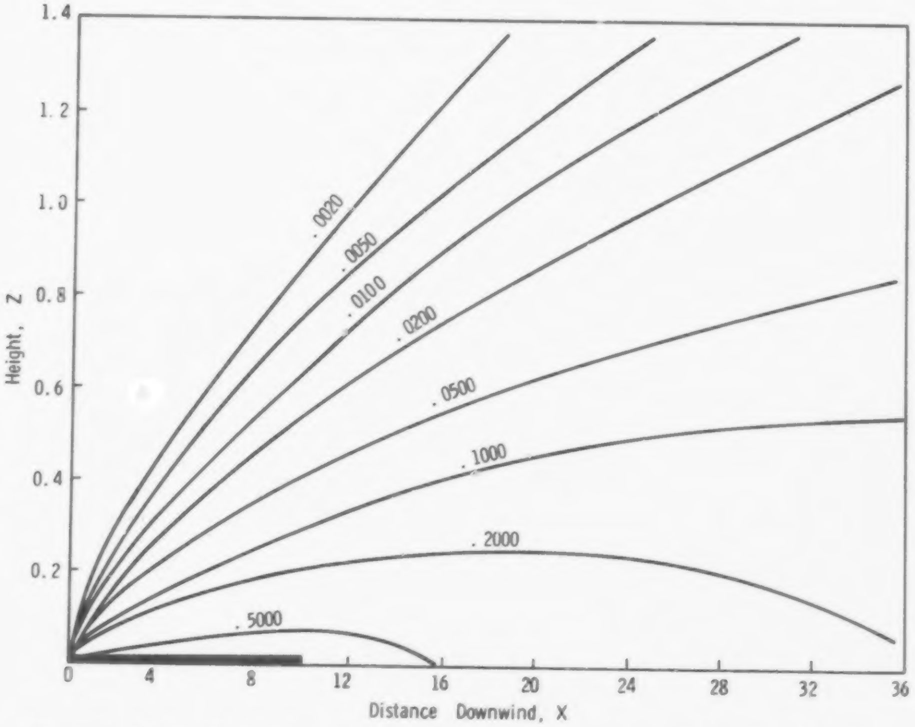

Figure 6. Lines of constant, crosswind-integrated concentration in the X, Z plane. D = F = P = O. No inversion.

EXTENSION OF THE METHOD

Analog computation can be used profitably in solution of partial differential equations with up to three independent variables. In diffusion problems these will be time and two space variables or three space variables. In the case, say, of three space variables, x, y, and z, one of them, usually x, will be represented continuously by computer time. The other two will be represented by finite differences.

Arbitrary variation of any parameter as a function of any of the independent variables is readily accomplished. The function

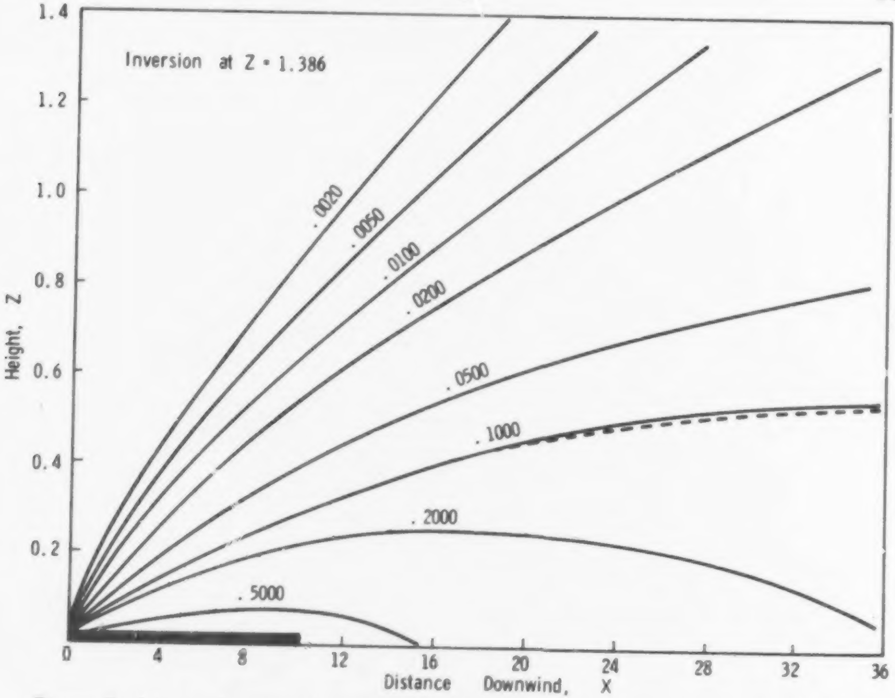

Figure 7. Lines of constant, crosswind-integrated concentration in the X, Z plane. D = F = P = O. Inversion at Z = 1.897.

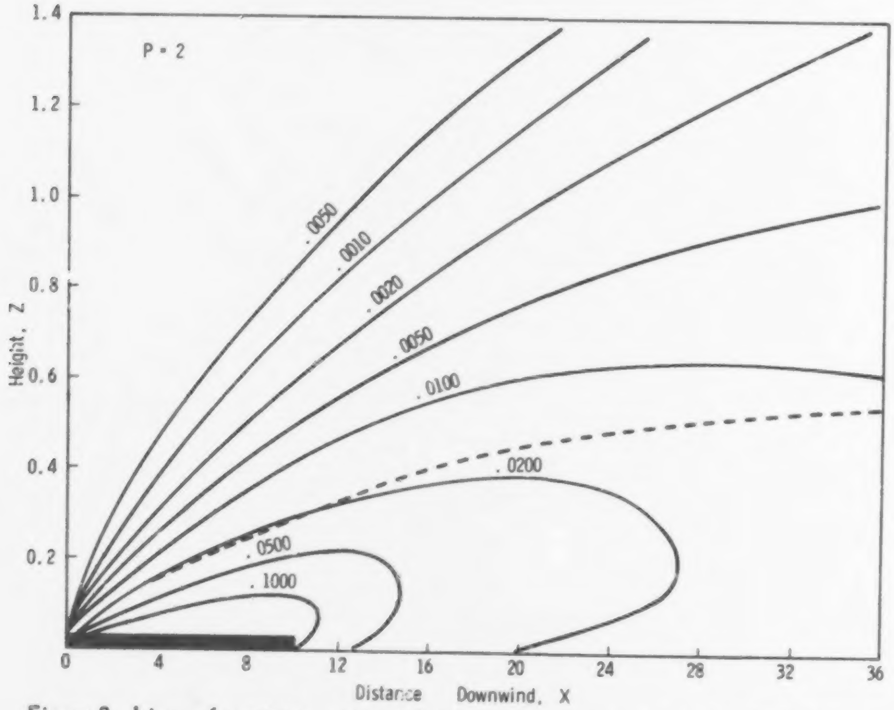

Figure 8. Lines of constant, crosswind-integrated concentration in the X, Z plane. D = F = O. P = 2. No inversion.

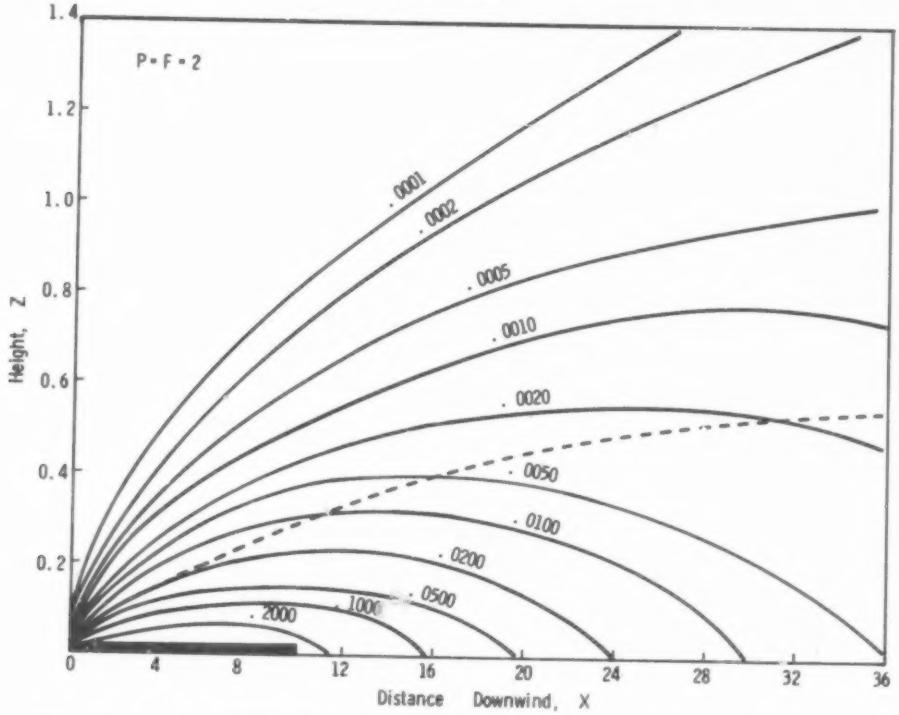

Figure 9. Lines of constant, crosswind-integrated concentration in the X, Z plane. D = 0. F = P = 2. No inversion

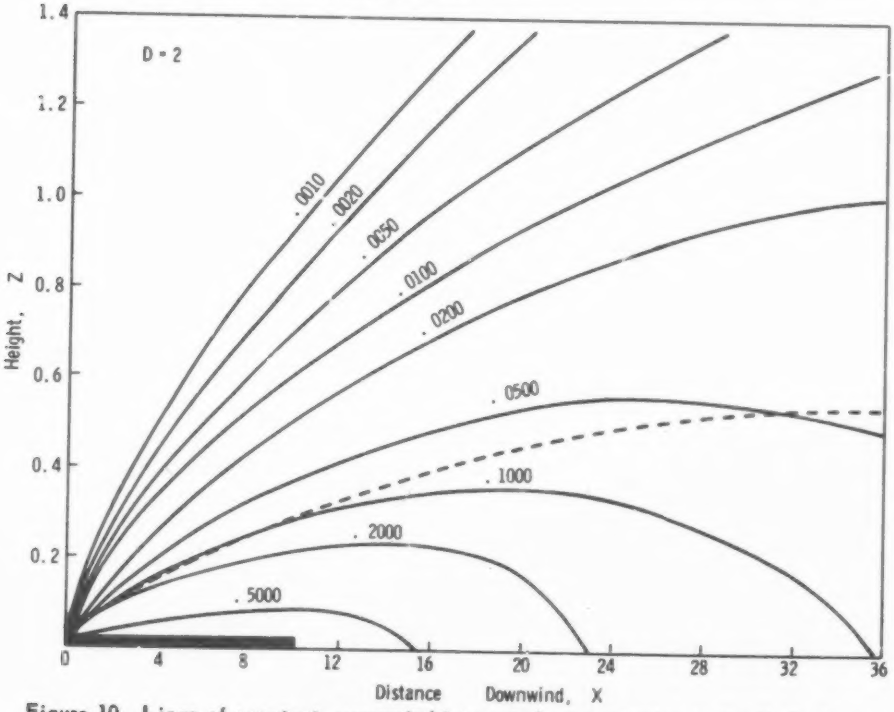

Figure 10. Lines of constant, crosswind-integrated concentration in the X, Z plane. D = 2. F = P = 0. No inversion.

may be in analytic, graphical, or tabular form. Boundary conditions of almost any desired form can be used, including multiple sources, ground reflotation of particulates, etc.

Not so readily accomplished, but still possible, is computation of the diffusion of the products of chemical reactions or radioactive decay in the atmosphere. It is possible to compute simultaneously the diffusion of the original substance and of the products of reactions.

The most severe restriction on this method is that the amount of equipment required increases with the complexity of the problem, so that each analog computer installation will have its own limit.

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3. Sutton, O.G., 1953. Micrometeorology. McGraw-Hill Book Company, New York

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DISCUSSION

MR. GIFFORD: Just to throw your last remarks into a little bolder relief, would you tell us, considering that you showed really a tremendous amount of computations, five or six complete fields for essentially different diffusion problems, about how long it took to program the machinery and to actually run off these solutions?

MR. BROCK: The question is a little difficult to answer because it happens that the problem is similar to a previous one that I did, but I think that programing the machine itself takes very little time. Designing the particular circuit would take perhaps an hour. It would take several hours to compute the coefficients for the various parts in the problem. It took me longer actually to decide how the boundary condition ought to be set up than to do all the rest of the work combined.

Running the problem doesn't take very long, because we set it up so that the particular solution is run out in about 15 minutes, and it is plotted out in graphical form for us. I then replotted in the form that you saw to make it a little more compact. So this work took me about two weeks, most of which was spent worrying about how the boundary condition ought to be set up.

MR. GIFFORD: It seems to me that in connection with urban pollution problem and area sources, there are essentially two separate problems, of which you have treated one. In the one problem you have an area source, and this would correspond somewhat to the megalopolis problem, where you are interested maybe in the next state or the next town, that is, what is coming from a large area upwind.

For the other problem you really don't care very much about what happens outside of town but you are extremely concerned about what goes on within the area source. And I wondered if you had given any thought to the simulation of this second problem.

MR. BROCK: Essentially there is a difference in scale, although when you deal with what is happening immediately within the source, so to speak, you have to be more careful about the simulation of the source. I think that could probably cause more trouble than anything else. It is reasonable to assume that the source is constant over a circular area, when you get far enough away from it. Up close you would probably have a series of point sources, and the problem then it to simulate these. If you have a field of point sources you must produce this electrically, and inevitably it would come down to a question of resolution. There is a limit to how fine a resolution one can get in analog computation. It is usually determined by the amount of equipment. However, it is like treating the problem of multiple sources, where you have a scattering of sources. I think that we could reasonably do something with this.

MR. GIFFORD: I might remark that we have just begun to think about this as a result of the very interesting visit that we had from Mr. Brock at Oak Ridge. We can't get it on the computer until December. But as a first approach, what we did was to apply a mathematical coordinate. This is really what I wanted to ask you about.

To get the detail in the city, we are going to change coordinates from X and Y to R and S, where $R = 1 - E^{-x}$, and $S = 1 - E^{-y}$. That means that when $x = 0$, say, than $R = 0$, and when $x = \infty$, $R = 1$, and when $x = 1$ it turns out that $R = \sim 0.8$. That means that if you apply this transformation then you can put most of your equipment inside the city and not worry too much about what goes on in the suburbs or in the next town. We don't have any results, but if you have any words of wisdom for us, I would be glad to hear them. Do you think we will get anywhere with that kind of approach?

MR. BROCK: I am sure that you will. The computers are of immense flexibility. You really can do almost anything that you want to do, if you persevere long enough.

This is an excellent transformation. Of course, the one that I used to reduce the z axis from infinity down to something finite that I could handle, and turning it around and applying it to X or Y is very much the same thing. You simply explode your scale then, which can be done very easily.

I would be very much interested in seeing the results on this, because I think you do have a good approach.

MR. LARSEN: Do you believe that a time-sharing of analog computer components would be a feasible method of cutting down on the amount of equipment needed for a three-dimensional simulation of air pollution over a city?

MR. BROCK: We have been considering this problem recently. There have been two innovations in the analog art recently. One of them is time sharing -- well, both of them are time sharing in a sense, and they have very earnest proponents. Now, so far as I know, and I have been in contact with some of the leaders in this field, this has not yet resulted in anything that can be brought to bear on our problem. It has been used in other problems, which can be described as something essentially like the diffusion equation. But in other things, such as fluid flowing through a pipe, for example, this time-sharing business has worked. The leaders in the field as of August of this year, and by leaders I mean specifically Professor Howe of the University of Michigan and some people from the West Coast, have agreed that at the present time this time-sharing could not be applied to the problems we have in meteorology. The problem seems to be that when you time share you introduce more errors, and as you do more of this to save on equipment, errors multiply and grow to the point that the computation becomes useless. I don't want to go on record as saying that this won't work in the future, but as of the present it does not seem to.

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MR. LARSEN: So if you wish to simulate pollution, say, over Cincinnati and from all points and from multiple sources you would still require hundreds of analog components to simulate a whole town at one time.

MR. BROCK: It depends on the detail you want. If you want to go into all the gory detail at once, then yes -- it would take an awful lot of equipment. But by no means would it completely solve the problem of handling partial diffusion by analog computers.

Dispersion Calculations for Multiple Sources

FRANCIS POOLER, Jr., *Weather Bureau Research Station, Laboratory of Engineering and Physical Sciences, R. A. Taft Sanitary Engineering Center, Cincinnati, Ohio*

Summary

Several ways in which multiple sources may be collectively described are examined, together with appropriate diffusion formulation. Since the main objective in developing models to calculate concentrations is to eliminate the necessity of direct air quality measurements, a pragmatic approach is recommended, both to simplify the required calculations and to incorporate diverse observations of pollutant behavior into the models used. Some possible uses of the calculations are discussed, and necessary further observations suggested.

Calculation of pollutant concentrations from the numerous sources in urban areas is a difficult task. We probably will never be able, or even be asked, to derive models capable of explaining all possible variations of concentrations over an area, because no one has any use for such detailed information. What are desired, and likely will be for some time to come, are values of calculated concentration that show details comparable to those that can be observed. The apparent objective in making calculations is thus, essentially, to be able to calculate values of concentration that match measured values. The ultimate objective is to develop means of calculating concentrations to supplant direct measurements.

This general objective can be divided into at least five categories, corresponding to the uses that might be made of calculations. The categories that occur to me are:

1. To estimate concentrations for particular times and places, for correlation with some known effect.
2. To estimate the contributions to the total pollutant loading from particular classes of sources: from different source areas, or from different kinds of sources within the same area.
3. To delineate the spatial distribution of concentrations.
4. To estimate the variability of concentrations for averaging times less than the sampling interval of the instrument used.
5. To estimate extreme concentrations that could occur at a given location.

As a general statement of the calculation problem, we are trying to determine the concentration at any point in space and time. The concentration is made up of the contributions from a field of sources, with this source field a function of the space and time coordinates. The contribution of concentration from any point in this source field is the product of the field strength and a spatial probability distribution function, which itself varies with time. Symbolically,

$$\chi(x, y, z, t) = \int_x \int_y \int_z \int_t Q(x, y, z, t)\, D_{xyz}(t),$$

where Q is the source strength of a point in the 4-dimensional field of space (x, y, z) and time (t) and D is a spatial distribution function, also dependent on time. The total concentration at a point is obtained by integrating over the 4-dimensional field. It may be noted that the source field is to be integrated, and not the concentration field.

In any real case we might be dealing with, we will never be able to specify either Q or D precisely and totally. We are forced, by practical necessity, to approximate the sources by a collective source description, and to approximate the probability density fields by a collective probability density. In other words, we are attempting to describe a highly complicated matter by making some simplifying assumptions, in order to derive mathematical analogs that can be used to estimate concentrations. In any analogy, comparison is made only between limited parts of the two subjects compared; in an analogy of multiple-source dispersion, one must choose the portion of the problem that is to be most closely described by means of the analog. The portion to be described is determined primarily by the purpose in making the calculations. In other words, there is no all-purpose model that can be used to satisfy all the uses to which multiple-source dispersion calculations might be put. The particular model used will depend on three factors: (1) the use to be made of the results; (2) the source data available; and (3) the meteorological data available.

The models that can be employed fall into three general classes, which can be named according to the source description employed. These classes I shall call the cloud-source model, the grid-point-source model, and the area-source model. In the cloud-source model, the emissions from groups of sources are followed forward in time, and the concentration from any source grouping can be calculated for as many points as desired. In equation form,

$$\chi_p (t) = \sum_i \int_t Q_i (t)\, D_{xyz} (t) .$$

The source grouping can be considered as an emitted cloud per unit time, the cloud having some definable initial probability density. The subsequent travel and spread of the instantaneous cloud can be approximately described in terms of any available meteorological measurements, so that it is not necessary to assume spatial or temporal uniformity in either the mean flow or the turbulence processes. The amount of calculation necessary with this kind of model increases in direct proportion to the number of source clouds used to describe the sources, since generally both the initial cloud distributions and the subsequent mean motions and diffusion rates will be different for each cloud. When it is obviously necessary to consider a varying field of motion, which usually will be the case when pollution must be followed for at least an appreciable fraction of a day, this kind of model is probably required. However, if such long travel times must be considered, the exact details of the real source geometry become rather unimportant, so that it will generally be possible to keep the source clouds limited to a manageable number. Dr. Frenkiel used this kind of approach with, I believe, a digital computer to estimate concentrations in the Los Angeles basin using clouds for his model. This same general approach can, of course, be used with a limited number of individual sources, in which case the contribution from each source to a point can be calculated individually by a conventional formula.

In the other two kinds of models, both temporal and horizontal spatial uniformity of motions are assumed, so that the relative dispersion from source to receptor doesn't depend on the actual location of either, but only on the relative locations. In the grid-point-source model, a series of sources of identical geometry are used to represent the real source, so that the spatial variations of source strength can be simulated to an accuracy determined by the spacing of the grid-points. The concentration at a point is then determined as the sum of the contributions from each source point, or

$$\chi_p = \sum_i \frac{Qi}{u} D_{yz}(x).$$

The most practical use of this kind of model is to calculate concentration patterns for an area, and usually it will be desirable to obtain as much detail in the spatial variation of concentration as is available from the source description. Thus it is easiest to use this model to calculate values for a grid of points with the same spacing as the source grid. A grid of D values can be calculated, the products of Q and D at each grid point obtained, and these products added to calculate the concentration for one point. The grid of D values must then be shifted relative to the source grid, and the arithmetic repeated, to obtain concentrations for each point of the grid. Thus, the amount of simple arithmetic necessary is proportional to the square of the number of grid points. The easiest, cheapest, and most accurate way to do such arithmetic is with the aid of a digital computer.

A somewhat simpler source grid can be devised if concentrations at only a small number of points are desired, by spacing the grid points in such a way that the relative contribution from each source point to the receptor point is about the same; this can be done by spacing the points so that their density is an inverse function of distance from the receptor point.

The third model is the area source: the concentration at a point is determined as the integrated contribution from the upwind source area, or

$$\chi_p = \int_x \frac{Q}{u} D_z(x)$$

The assumption is made in such a formulation that the source area is sufficiently extensive in the crosswind dimension that it can be treated the same as an infinite crosswind source. As Mr. Brock showed, you could also make the distribution function two-dimensional rather than one-dimensional as shown. In view of the fact that there has been quite a bit of coverage of area sources by Mr. Brock and Dr. Neiberger, and by Dr. Schmidt yesterday, there is no need to go into any further detail to show the use that might be made of such calculations.

When it comes to setting down some exact expression for a model, three steps are required. The first is a visualization of the entire dispersion process that is to be described. This requires a good imagination, for we will rarely be able to actually see more than small glimpses of the real situation, and we must fill in the greater part of the total picture with imaginary plumes, telescoping time scales, and other devices.

Some attention must also be given to the source inventory that will be used, for the way in which the sources are to be collectively described is partially dependent on the way the dispersion is to be treated, and the dispersion will very obviously depend on the geometry of the sources. It will be necessary to consider what purpose the calculations are to serve, what kind of detail will be available from the source data, and what sorts of meteorological data will be available. From these considerations, we must settle on the type and general form of the model to be used. The source data can then be adapted to the model.

The second step is to break down the total dispersion process into smaller components that can each be described by means of some mathematical expression. For this step, I think the best thing to do is look out the window, or sit on top of Mount Royal, perhaps to watch the auto-correlation of velocity, or the growth and decay of eddies, or whatever it is that one chooses for describing diffusion. This step requires the ability to be a good observer. I think both the first and second steps, the visualization and the observation, require the capability of a meteorologist, and therefore I wouldn't trust a model not made up by a meteorologist.

The third step is to use the meteorological measurements that may be available to indicate the dispersion that has been observed and described. I think a great deal of confusion can be avoided if we recognize that there is no such thing as a definitive set of meteorological measurements that will describe dispersion for even the simplest of circumstances. We must therefore use available meteorological data as indices of dispersion conditions, and not regard them as diffusion measurements. If we choose to use a meteorological parameter as a continuous index, rather than as one element of a discrete classification system, it will be possible to end up with some extremely odd dimensional units for numerical coefficients, even though the original form of an equation is dimensionally logical. This step requires a very careful judgement, and probably few observers would choose identical values to describe the same process.

Even with rather scant meteorological data to work with, it will be possible to devise some elaborate formulations that provide a quantity of doubtful detail. Since these details cannot be checked, and may not be valid to start with, it will often be possible to simplify a formulation without any real loss of accuracy. It will often be instructive to plot curves of calculated concentration versus distance from a source, using linear scales, to see what the influence of varying parameters in a formulation may be. In this way, it may turn out that a large error factor really doesn't matter, because the erroneous contribution is only a small fraction of the total from all sources. The degree to which a formulation is simplified will thus depend in part on the formulation itself and on the use to be made of it.

Since the form of an equation as used will depend on the means available for making the calculations, I don't believe there is much point to setting down specific formulae. With an area-source model, it is easiest to set up some expression that can be integrated analytically or electronically; with a grid-point source model, quite unwieldy functions can be used, since the expression need be numerically evaluated only for discrete points;and with the volume-source model, dispersion by the mean flow may mask some of the smaller-scale diffusion processes, so that mass continuity of the mean flow will be a primary requirement of a formulation.

Multiple-source dispersion calculations at present involve too much guesswork and arbitrary extrapolation to be regarded as having a scientific merit, and therefore I don't think they should be judged by scientific standards. Improvements will come about by narrowing the margin of uncertainty in our estimates of dispersion parameters and by increasing our knowledge of the relationships between dispersion and available measurements. The greatest area of uncertainty is in the area of generally greatest significance in determining pollutant concentrations in urban areas: we have very little data concerning the vertical distribution of mean flow and turbulence, or of pollutant stratification. We also lack a physical basis for tying such data together, i. e., our theories are incomplete. We know little concerning the ultimate disposition of pollution; we can't very well say where something is going unless we first know what it is, and this requires attention to the physical and chemical forms in which the pollutants exist in the atmosphere.

In spite of these inadequacies, I think we can, at present, make calculations for limited situations that are sufficiently accurate to serve a useful purpose. If such results justify our inexact methods we can always incorporate new findings and more complete theories into the methods, and thereby extend the utility of such calculations.

DISCUSSION

CHAIRMAN NEIBERGER: I have a feeling it might help some of the people here if you will describe how one would go about getting the D function.

MR. POOLER: Well, this is the thing I had in mind when I said, first look out the window. I don't believe there is any general way to go about it, primarily because it depends on the model you are using. For instance, if you are interested in dispersion over scales of several miles, which would be an urban area diffusion problem, you would have to come out with some distribution function that fit what the atmosphere was actually doing. This is the main requirement, and how you actually do it, I think requires imagination more than anything. There are certainly numerical measurements or calculations from some of the work that Dr. Hilst has done, as an example, or some of the work from large sources, our TVA studies, where we can see the dispersion measurement over fairly large scales, and we can use these numerical data as a beginning point. But I think the problem is that there is so little that we know about large-scale diffusion that at this point we simply have to make up a great deal.

DR. GIFFORD: There are really three parts to this problem. First, you have got to get the material into the air, and then there is the part you have been talking about, which is carrying it through the air, and then the other part, which concerns the effect on people. Also there is the problem of measuring concentrations after some residence time of materials in the air. Since you highlighted the uncertainties and difficulties and general unsatisfactory nature of the second of these, I wondered if you would be willing to hazard a guess as to whether the atmospheric contribution is more or less uncertain, for example, than our present knowledge of sources and of concentration measurements? In other words, does it make much difference whether we are a little uncertain about it?

MR. POOLER: This is a very good point to bring out, because I think at the present time the estimates we can get of the sources and also the accuracy of many of the concentration measurements are probably about the same order of accuracy as our dispersion calculations -- of equal uncertainty in all three areas.

MR. HILST: You are not suggesting that on this account it is worthwhile to take less than the best we can get?

MR. POOLER: We should all aim for perfection, but we will never know if we have reached it.

Some Effects of City Structure on the Transport of Airborne Material in Urban Areas

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Summary

Transport of airborne material in urban areas is compared to the transport mechanisms observed and calculated for open areas. The effects of urban areas in modifying general weather patterns are examined, with emphasis on the effects of specific location, size of the urban area, wind speed and cloud cover, and vertical temperature gradient. Meteorological and air pollution surveys conducted in several cities are reviewed, and conclusions based on these surveys are presented. The degree of loss of particulate matter by impaction on exposed surfaces in urban areas is considered; theoretical and experimental impaction data are reviewed.

There is reason to believe that the transport of airborne material in urban areas, particularly under certain meteorological conditions, might differ substantially from the transport that has been observed in open areas. Buildings and other structures increase the surface roughness, thereby enhancing atmospheric diffusion associated with mechanically induced turbulence. In addition, the large number of surfaces within an urban area affords a potential loss of particulate airborne material by impaction processes.

Unfortunately the type of experimental data I would like to present to illustrate these and other effects are not now available. What are needed, of course, are quantitative observations on the diffusion of material within cities for direct comparison with measured diffusion in open areas. To be meaningful these diffusion studies require an air sampling network on a suitable scale, together with a controlled source of tracer material that can be emitted in known amounts and, if particulate, in a prescribed particle-size range. Collateral meteorological observations on a scale commensurate with the travel distances are essential. Results from this type of investigation are a necessary starting point for the computer techniques suggested by Hilst at this meeting, if the results of these computations are to be representative of actual transport within cities.

In the absence of suitable field data, one must fall on indirect evidence that suggests possible differences in the transport

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of airborne materials within cities as compared with open areas. Perhaps the most pertinent line of evidence is the well-established fact that air temperatures within cities are significantly different from those in surrounding open areas. The differences are evident both in the horizontal temperature distribution near the ground and in the vertical temperature gradient.

The fact that cities are noticeably warmer than their surroundings has been known for over a century based on records taken from fixed stations inside and outside of certain cities.[1, 2, 3] The first measurements of temperature distribution at ground level within a city were obtained by Schmidt in Vienna[4] using equipment carried in a car. A similar technique was used by Sundborg[5] to obtain comprehensive measurements of air temperature throughout the city of Uppsala. The first indication that the vertical temperature gradient was modified in an urban area was obtained by Blachin and Pye[6] during their investigation of the temperature patterns in Bath, England, which lies in a steep valley. In a number of cases nighttime temperatures taken from the hillside showed little or no inversion over the city, although inversions were established within the valley on either side of the city.

With the above surveys as background, a series of detailed measurements on urban modification of air temperature was undertaken by the Aerosol Laboratory, Stanford University. The results have been reported by Duckworth and Sandberg[7] and have been fully described by Mitchell and others at this meeting.

A few comments regarding the objectives of these surveys may be of interest. Since modification of air temperature by a city is less pronounced during the day than at night, primary emphasis was given to nighttime observations. In designing the program four points were given consideration. First, the attempt was made to determine by refined techniques whether temperature effects observed thus far were characteristic of cities in general or whether these phenomena were peculiar to specific locations. The fact that urban temperature modification had been noted in several communities in earlier years certainly suggested that this was a general characteristic, but additional data obtained with improved equipment seemed desirable.

Second, the effect of city size on the extent of urban modification had not been investigated systematically. Accordingly, measurements were made in San Francisco, San Jose, and Palo Alto to represent large, intermediate, and small cities located close enough within the Bay Area to have similar over-all weather conditions. Conditions are particularly similar during the summer months, when the study was undertaken.

Third, additional information was needed to establish the effect of wind speed and cloud cover on urban temperature modification. On the basis of available data these two factors appeared to be the most important over-all weather factors controlling the urban effect.

Finally, and perhaps most important, measurements of vertical temperature gradients taken concurrently with the horizontal temperature traverses were needed. It is doubtful that the hillside observations taken in Bath were truly representative of the free air temperature gradient. Accordingly, wiresounde temperature measurements were made within and outside each of the three cities in conjunction with the ground-level measurements taken with sensors mounted on automobiles.

Since the investigation in the Bay Area was completed, DeMarrais has reported on vertical temperature gradient observations in Louisville.[8] These urban-area gradients were compared with typical open-area vertical gradients obtained in Idaho and New England. The findings of DeMarrais are in accord with those described by Duckworth and Sandberg.

Typical examples of nighttime temperature surveys in San Francisco and San Jose have been shown previously. (See Figures 1, 2, and 3 - Mitchell) Air temperature is highest in the most built-up area and lowest in the open areas. A similar pattern was found for Palo Alto. In all three cities maximum temperature differences were associated with light wind and clear sky, and under comparable conditions the differences were greater the larger the city. Thus in order of decreasing city size, the maximum observed temperature differences between urban and surrounding areas were 20°F, 14.2°F, and 12.6°F. Representative temperature differences in the three cities were approximately one half the maximum values.

Figure 1 shows one example of temperature gradients observed in built-up and open areas in San Francisco under conditions favorable for the development of a moderate temperature differential across the city. Typically, the strong inversion associated with the open areas is absent within the city at low level. In the example shown, the gradient in the built-up area is essentially neutral below 100 feet and isothermal aloft, with a slight inversion at 125 feet. In many cases the gradient taken within the city showed a marked inversion at about two building heights above the surface, with neutral conditions below.

From the several trials conducted in the three Bay Area cities coupled with earlier and more recent observations obtained

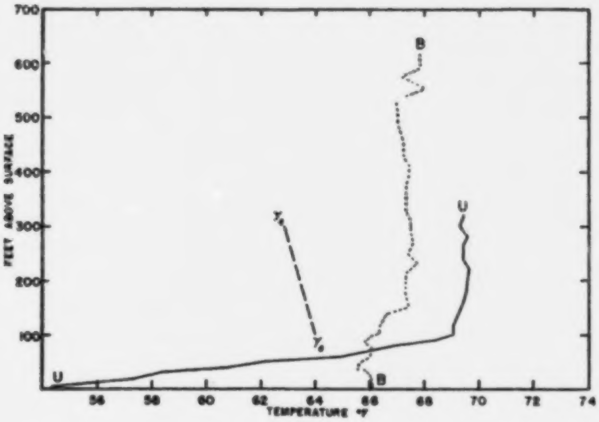

Figure 1. San Francisco wiresounde data for 2110 PST 26 March 1952 showing typical vertical temperature gradients in a built-up area (B) and undeveloped area (U) for clear sky and light wind conditions at night.

in other cities, certain conclusions can be drawn regarding nighttime urban modification of air temperature and vertical temperature stability. The urban modification is likely to be found in all cities provided the sky is clear and the wind speed is not too great. In a given city the horizontal temperature patterns are remarkably reproducible. Under conditions favorable for marked temperature differential within the city, an inversion develops in open areas but not within the city. The atmosphere is neutral from the surface to approximately two building heights and may be stable above this level. These changes in air temperature are more pronounced the larger the city and the greater the degree of urban development.

As Mitchell has already pointed out, the higher air temperature within the city results from the stored heat within the buildings and paved surfaces. Because the warm surfaces radiate to each other rather than directly to the night sky, the rate of heat loss is much less than from a flat surface in an open area. In addition, a significant amount of heat can be provided by normal fuel consumption. Thus in one of the San Francisco surveys, the calculated total energy required to maintain the observed temperature difference was 3.0×10^{10} Btu per hour. Stored heat provided an estimated 1.8×10^{10} Btu per hour and from an inventory of fuel consumption an additional 0.9×10^{10} Btu per hour could be expected. In this case the known available total heat source was 2.7×10^{10} Btu per hour, which is in reasonable agreement with the estimated 3×10^{10} Btu per hour required.

From the standpoint of atmospheric diffusion within cities, the urban temperature modification tends to reduce the extreme range of conditions expected. Lapse conditions will be found during the day if such conditions exist in the open. Inversion conditions in the lower layers within a city are not likely at night, however, and in any case will be less well-developed than in open areas. Thus a strong inversion in open areas associated with light winds and clear sky are accompanied by neutral conditions within built-up areas. If the sky is overcast or the wind speed is high, the urban temperature differential will be eliminated and neutral atmospheric stability can be expected both inside and outside the urban area. As a consequence of the urban temperature modification therefore, atmospheric temperature stability within a city is generally limited within the range of neutral to lapse conditions rather than inversion to lapse, as found in the open. Accordingly the transport of airborne material within cities may be expected to show less variability than that in the open.

If the airborne material is composed of particulates, some of the material may be lost by impaction on the large amount of surface to which airborne material is exposed in an urban area. The magnitude of this loss can be estimated by use of experimental data obtained in connection with laboratory studies on particulate impaction. An airborne particle approaching an obstruction may contact the obstructing surface and presumably be retained, if the particle has sufficient momentum to cross the streamlines formed around the obstruction. If its momentum is not sufficient, the particle will be carried by the air stream around the obstruction and there will be no impaction. As shown by Johnstone and Roberts,[9] momentum considerations can be used to define a dimensionless parameter, K, which in turn may be directly related to particulate impaction efficiency. Specifically,

$$K = \frac{1}{18}\,\frac{d^2 u \rho}{D \mu} \qquad (1)$$

where d = particle diameter
ρ = particle density
u = air speed relative to obstruction
μ = viscosity of air
D = minimum crosswind dimension of obstruction

Theoretical and experimental particulate impaction data reported by Ranz and Wong[10] indicate that no impaction is expected for K values less than 0.05. For a nominal wind speed of 10 mph (500 cm/sec), a particle diameter of 2 microns, and density 1 gm/cc equation (1) becomes

$$K = \frac{6.16 \times 10^{-3}}{D}$$

Therefore, in order that K exceed the limiting value of 0.05, the value of D must be less than 0.12 cm. Obstructing surfaces having a minimum dimension greater than this value will not be effective collectors by the impaction process in moderate winds unless the particles are substantially larger than 2 microns. Thus buildings and other structures will not be expected to collect a significant amount of particulate airborne material.

Although losses might be expected on small surfaces such as wires and foliage, two factors tend to minimize the over-all loss on such surfaces in city-wide transport. First, if the foliage is dense enough to cause significant removal by impaction, the wind speed and likewise the impaction efficiency will be reduced. Second, if the wind speed is high, mechanical turbulence will distribute the airborne material aloft and a smaller percentage of the total will be in lower layers and in contact with obstructing surfaces.

At the outset of this discussion I indicated that quantitative data on the transport of material over cities are not now available but I must make one exception. Neiberger conducted five daytime experiments in Los Angeles using a particulate fluorescent tracer[11] to investigate the reliability of trajectory analysis from available meteorological data.

In trial 5 all of the tracer material was carried across the single sampling arc, and further, the arc was wide enough to bound the airborne tracer on each side. Therefore the results from this trial can be used for a quantitative comparison between the amount of material released and the amount found at the sampling position.

Briefly, the trial was conducted as follows. A total of 2400 grams of fluorescent tracer was released between 5 and 6 a.m. from a point source at Compton Airport, as shown in Figure 2. From appropriate calibration data, it was known that each gram of tracer contained 5.5×10^{10} fluorescent particles, hence the total number of particles released was 1.3×10^{14}. A total of 23 samplers were located along an arc approximately 13 miles from the source. Air samples were collected on membrane filters. Any fluorescent particles present in the air sample were retained on the filter surfaces and were readily identified and counted under ultraviolet light. Filters were changed at hourly intervals to determine the time of tracer arrival and the time required for the tracer to pass the sampling arc.

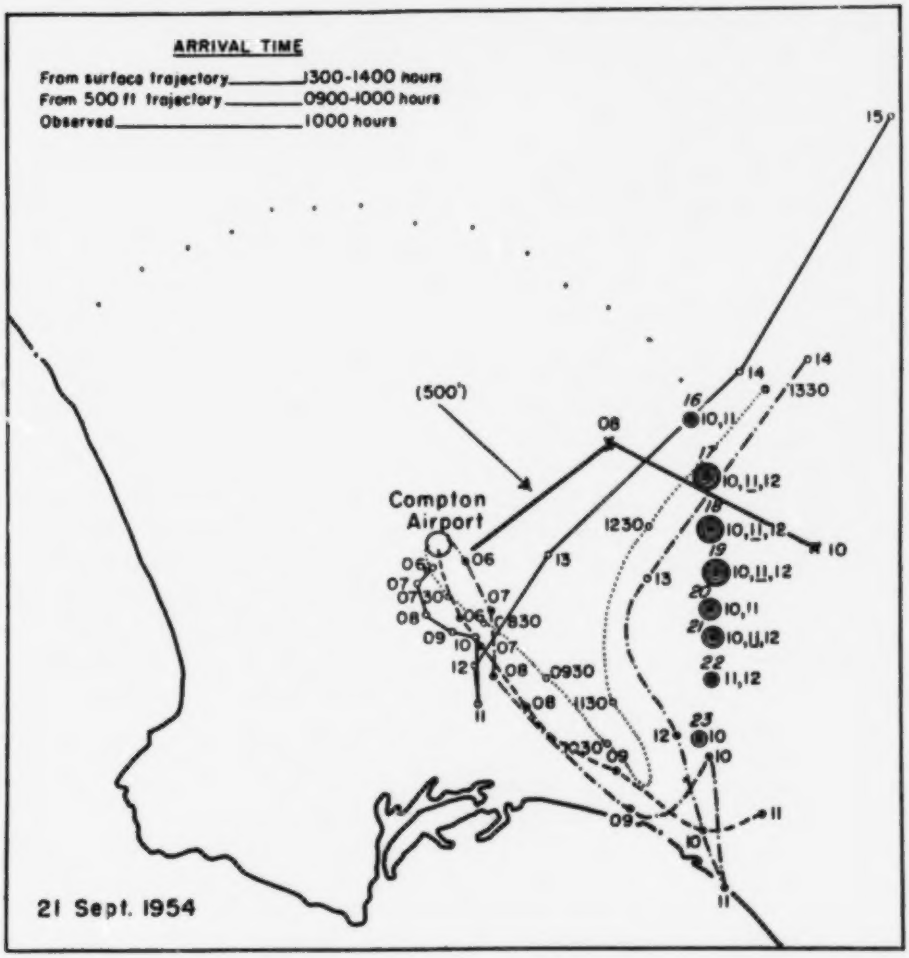
ARRIVAL TIME
From surface trajectory 1300-1400 hours
From 500 ft trajectory 0900-1000 hours
Observed 1000 hours
(500')
Compton Airport
16 10,11
17 10,11,12
18 10,11,12
19 10,11,12
20 10,11
21 10,11,12
22 11,12
23 10
1330
1230
1130
1030
0930
0830
0730
21 Sept. 1954

Figure 2. Results of fluorescent particle tracer test No. 5 conducted by Neiberger in the Los Angeles Basin. Tracer was released at Compton Airport; samplers were located on an arc approximately 13 miles distant from the source. Positive counts were obtained at stations 16 through 23; each circle at these stations represents one power of ten in particle count. Numbers to right of stations show hours when tracer particles were collected. Surface wind trajectories by several analysts are included together with one 500-foot level trajectory. (Air Pollution Foundation Report No. 7)

During the first 3 hours after the release, winds were light and variable. The tracer moved an estimated three miles in a southeasterly direction then later in the morning reversed its direction. Subsequently, the wind speed increased and the tracer moved steadily across the center of the sampling arc at 6 mph. The total number of particles collected at each station is given below; in Figure 2 each ring around the station represents particle numbers collected in powers of 10. Sampling rate was 8.75 liters/minute at station 23 and 7.5 liters/minute at all other stations.

Sampling Station No.	Total Particle Count	Sampling Station No.	Total Particle Count
15	0	20	864
16	60	21	346
17	1963	22	98
18	3352	23	42
19	1541	24	0

Before the tracer reached the sampling arc, surface heating created unstable conditions from the ground to 1000 feet. A strong inversion at the 1000-foot level effectively stopped further mixing above this height. Under these conditions it is reasonable to assume that mixing was sufficient below the inversion to produce a uniform vertical distribution of the tracer between the surface and 1000 feet. Thus the amount of tracer recovered at ground level can be used to compute the total amount of tracer passing through a vertical plane extending from the sampling arc to a height of 1000 feet. On the basis of this assumption the total number of particles crossing the sampling arc from the ground to the inversion layer is 1.1×10^{14}. The expected value based on the total number of particles released is 1.3×10^{14}. In view of uncertainties in determining source strength, inversion height, and wind speed through the unstable layer, these two values are in excellent agreement. These results suggest that the proposed transport mechanism is reasonably correct and that there was no significant loss of particles in the course of 5 hours of travel over the city of Los Angeles.

Obviously, more information is needed before results such as these, obtained in one trial, can be generalized. If observations indicate that marked atmospheric stability in the lower layer over a city is normally absent, however, then vertical mixing of airborne material can be expected both day and night. In this sense the presence of a city tends to simplify rather than complicate the problem of estimating behavior of airborne material in its movement over urban areas.

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DISCUSSION

MR. YOSHIDA: You mentioned that there were no losses by impaction on buildings. Have you made any estimate of the amount of tracers you may lose as a result of a diffusion process?

PROFESSOR PERKINS: Yes, we have made a fairly crude attempt at this and this loss appears to be extremely small. Much less than that by impaction.

DR. LANDSBERG: Professor Perkins, I have a question with respect to your d over D factor. That can be valid only at a certain limiting windspeed.

PROFESSOR PERKINS: You are exactly right. My point in presenting this was to depict a certain condition at 10 miles an hour. Of course, as windspeed goes up, the D value would also go up in proportion. At 100 miles an hour the corresponding value of D would be at 12 centimeters, but at 100 miles an hour one is not much interested in impaction.

MR. HOLZWORTH: We have seen the slides that were produced by Duckworth several times here, and you have mentioned that there were certain conditions under which one would get these temperature patterns, the heat islands. With respect to San Francisco, that area being rather windy and cloudy, we should point out that these pictures probably are not too representative of conditions that occur there often. Is that correct?

PROFESSOR PERKINS: Yes, in the sense that the measurements were made not necessarily to determine whether these were characteristic of San Francisco over, say, an appreciable period of time. They are characteristic of a large city, providing you have the clear conditions and low windspeed.

MR. HOLZWORTH: These were, indeed, rather specialized occasions in San Francisco, wouldn't you say?

PROFESSOR PERKINS: I don't represent the San Francisco Chamber of Commerce but we don't have clouds all the time. Of course, the stratus is a very common phenomenon during summer, but much less so in spring and fall.

DR. HEWSON: I would like to ask what might be the time variation of this rather uniform distribution of turbulence for a city. For example, don't we begin to get some stabilization, say, towards dawn?

PROFESSOR PERKINS: The temperature differences maintain their identity throughout the night; in San Francisco there is a difference all night long. In a small community, Palo Alto, the difference is less. So again it is a function of city size.

FROM THE AUDIENCE: In view of the comments about impaction and d over D, and comments about the effectivity and desirability of parks in metropolitan areas, would you care to comment on the effectiveness of parks in helping pollution problems?

PROFESSOR PERKINS: Well, my comments will be rather qualitative. If one intends to remove particles by impaction, it will have to be by foliage, since it takes small surfaces to do it. If the foliage is dense enough to make appreciable reduction in the concentration of material in an area of 1 or 2 kilometers, then the windspeed simply couldn't be maintained. In other words, if you have a high density of foliage, you lose your windspeed, and therefore the impaction efficiency drops because it varies in proportion to the windspeed.

We have some reservations as to the possibility of removing particles effectively by this mechanism. One other consideration is that you remove only the material that passes through this lower layer. If the material is also distributed substantially above the lower layer then, of course, the percentage lost by impaction is going to be reduced.

MR. KALSTROM: In the studies in San Francisco and San Jose was there any attempt to differentiate natural differences from the effects of the city? In other words, were all of the observed effects due to the city or were part of them due to conditions that were there previously? I don't know how much building has gone on in San Francisco since 1952, but in both San Jose and Palo Alto there has been considerable building and enlargement of the city since that time. Would a new study show the same pattern or would it show the effects of the more recent building?

PROFESSOR PERKINS: San Jose, I am sure, would show a new pattern. There isn't the slightest doubt about it. And this is by virtue of the fact that not only has it expanded, but there has been an appreciable density increase in certain areas. A restudy of this area, I think, would show the effects that you mentioned.

Now, I think your first point was that you are trying to separate the effect of the city from the local climatology --

MR. KALSTROM: Pre-existing.

PROFESSOR PERKINS: Pre-existing climatology. I think San Jose might be a good example to illustrate this point. Were San Jose completely removed, and the flat area undeveloped or agricultural as it was in the past, I am sure you wouldn't find the kind of temperature discontinuity now observed in that area.

Source Configurations and Atmospheric Dispersion in Mathematical Models of Urban Pollution Distributions

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Summary

The bivariant normal distribution of airborne materials emitted continuously from individual point (small-area) sources is utilized as the basic mathematical model for atmospheric dispersion. The mathematical form of the variance terms in this model, as a function of travel distance or time, is reviewed. The integral form of these basic equations for multiple sources is then derived and examined for tractability under various source-distribution and dispersion conditions. Simplified conditions are utilized to obtain distributions of air pollutants for steady-source and meteorological conditions and these are presented to show the effects of concentrated versus widely dispersed sources. The more general utility of the model in studying various source configurations under a variety of meteorological conditions and the restrictions that must be imposed for real sources and atmospheres are reviewed.

The problem of urban air pollution and its impact on the comfort, safety, health, and economic status of communities of people are, paradoxically enough, becoming better defined and more complex at the same time. Better defined as we discover the underlying biological, physical, and chemical processes at work; more complex as we recognize the multivariate nature of the problem and the sometimes subtle, sometimes bold interactions of the atmosphere, sunlight, multiple pollutants, and the distribution of sources of pollutants in establishing the patterns of exposure in the urban environment. A pollution problem exists only if there is a material or combination of materials that adversely affect at least one segment of a population; the effects are in themselves frequently difficult to define.

The work of many people in the many facets of air pollution has shown conclusively that the knowledge and understanding we require to cope with this problem, whether in urban planning or pollution control, must be derived as a consistent synthesis of the processes of pollution generation and emission, atmospheric transport and diffusion, and interactions between the pollutants and the receptors. It is the purpose of this paper to present a method for synthesizing the first two of these, source variables and atmospheric variables, by way of a mathematical model and in the context of the urban pollution problem. This model is restricted to steady-state meteorological and source conditions and predicts average concentrations.

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THE MODEL

Consider a Cartesian coordinate system with an arbitrary origin but fixed in the earth, with the x axis oriented along the direction of the mean wind, the y axis oriented horizontally crosswind, and the z axis oriented along the vertical. At a point (ξ, η, ζ) we place a continuous, steady point source of strength $Q(\xi, \eta, \zeta)$. The average concentration of the material emanating from this source when it reaches the point (x, y, z) is $\chi(x-\xi, y-\eta, z-\zeta)$. We wish to specify $\chi(x, y, z | \xi, \eta, \zeta)$ in terms of $Q(\xi, \eta, \zeta)$, $(x-\xi, y-\eta, z-\zeta)$ and the parameters that characterize the dispersive capacity of the atmosphere. For this purpose we shall assume that the distribution of χ in the (y, z) plane is bi-variant normal. Then

$$\chi(x, y, z | \xi, \eta, \zeta) = \frac{Q(\xi, \eta, \zeta)}{2\pi \bar{u} \sigma_z \sigma_y} \exp\left\{-\frac{1}{2}\left(\frac{y-\eta}{\sigma_y}\right)^2 - \frac{1}{2}\left(\frac{z-\zeta}{\sigma_z}\right)^2\right\} \quad (1)$$

where $\sigma_y{}^2$ and $\sigma_z{}^2$ are the variances of this bi-variant normal distribution and $\bar{u}$ is the mean wind speed at the source. We shall assume further that $\sigma_y{}^2$ and $\sigma_z{}^2$ are functions of $(x - \xi)$ only for a given meteorological condition. (The functional form of this dependence and/or the coefficients may vary from one meteorological condition to another.)

Equation (1) is the basic mathematical model from which we may simulate the multisource urban situation. One serious limitation of this model should be noted immediately: it does not properly account for the deposition of materials on the ground or obstacles, a limitation of some consequence. We shall circumvent this difficulty by assuming no deposition (perfect reflection), recognizing that this assumption tends to cause an overestimate of χ. This assumption requires us to multiply equation (1) by 2 when the source is near the ground.

Utilizing equation (1) we may now determine the total concentration at (x, y, z) due to all sources upwind of this point by

$$\chi_T(x, y, z) = \int_0^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{x} \chi(x, y, z | \xi, \eta, \zeta)\, d\xi\, d\eta\, d\zeta \quad (2)$$

The relative contribution of each source to χ_T is given by the ratio of equations (1) and (2), and since we have assumed a steady-state condition the dosage at (x, y, z) is simply proportional to the concentration at that point.

SOLUTION OF THE MODEL

Solution of equation (1) and integration of equation (2) requires the specification of $\sigma_y 2 (x - \xi)$ and $\sigma_z 2 (x - \xi)$. Various functional forms have been proposed and investigated. However, a discussion of the merits of each is beyond the scope of this paper. Rather, we shall choose Sutton's form, which is most appropriate to a neutrally stratified atmosphere, to illustrate the use of the model. Sutton's functional form for σ^2 may be written

$$\left.\begin{aligned} \sigma_y^2 &= a_y (x - \xi)^{p_y} \\ \text{and} \\ \sigma_z^2 &= a_z (x - \xi)^{p_z} \end{aligned}\right) \tag{3}$$

where a_y, a_z, p_y, and p_z are constants.

Solutions of equation (2) using these functional forms of σ^2 (or other forms) are quite readily obtained by numerical methods. The versatility of the model can be fully explored only when it is programmed for machine solution with arbitrary source specification. However, analytic solutions can be obtained for relatively simple source distributions and when interest is centered on the plane of the maximum concentration, $z - \zeta = 0$. These solutions are utilized here to illustrate the kinds of questions that can be directed to the model.

Let us consider three source configurations that illustrate possible modes of distributing the sources of an atmospheric pollutant through a city. These are (1) a continuous line source, (2) banded source strips, either singly or with non-source areas in between, and (3) a continuous, uniform source distribution over the area of interest. The resultant concentrations, as a function of distance from the upwind edge of the source area (or from the line source,) are shown in Figure 1. (Total source strength is conserved among these three source distributions.)

Inspection of Figure 1 shows, as expected, that the largest local concentrations are associated with the line source, the second largest with the banded source area, and the lowest with the uniformly distributed source configuration. Conversely, the maximum concentrations at large distances are ranked in reverse order. Clearly, if the maximum concentration is the determining criterion, one would choose the most widely dispersed source distribution possible. On the other hand, if certain areas can be reserved for "waste disposal" and it is desirable to keep the remaining areas as free of pollutants as possible, the sources should be compressed into the smallest possible area.

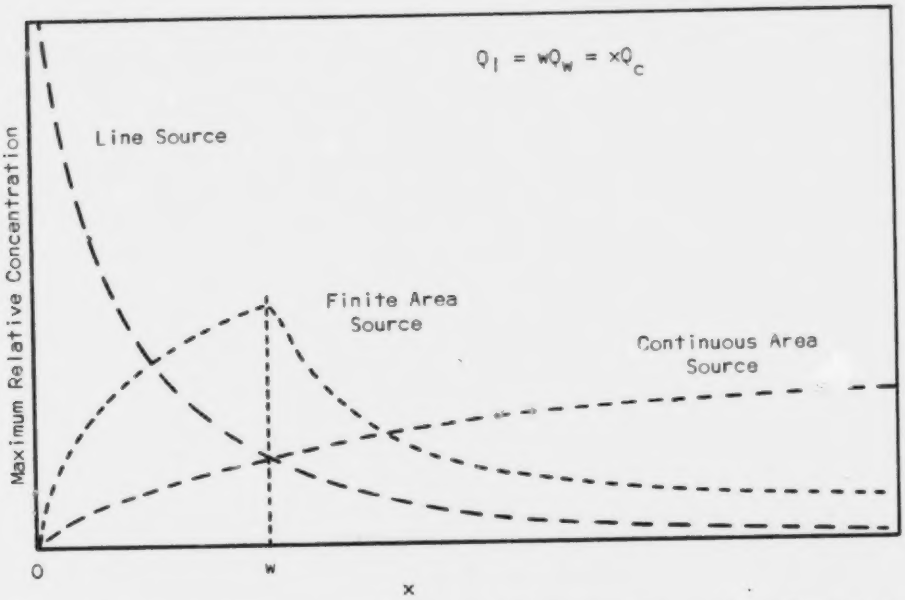

Figure 1. Maximum concentrations as a function of downwind distance from a line source, a banded source of width w, and a uniform source distribution, all of infinite crosswind extent.

Another criterion that may be established is, "What source distribution gives the minimum total dosage over some area of interest?" In the present steady-state model comparative dosages can be obtained by integrating equation (2) over the area of interest. With the infinite crosswind source distributions assumed for our exemplary models, the integration is over a downwind distance X from the line source or the upwind edge of the area sources.

Then

$$D_{i,X} = \int_0^X \chi_\tau(x)\, d\, x \qquad (4)$$

where χ_τ (x) is the distribution of concentration in the plane of the maximum (the plane of the sources), D is the dosage per unit time, and the subscript i specifies the source configuration (i = ℓ for line source, i = w for banded source, i = c for uniformly distributed source).

Solution of equation (4) for these source configurations yields

$$D_{\ell}, X = \frac{2Q_{\ell} X^{\frac{2-p}{2}}}{\sqrt{2\pi}\, \bar{u}\, A_z^{1/2}(2-p)}$$

$$D_{w}, X = \frac{4Q_{\ell}}{w \sqrt{2\pi}\, \bar{u}\, A_z^{1/2}(2-p)(4-p)} \left[X^{\frac{4-p}{2}} - (X-w)^{\frac{4-p}{2}} \right] \quad (5)$$

$$D_{c}, X = \frac{4Q_{\ell} X^{\frac{2-p}{2}}}{2\pi\, \bar{u}\, A_z^{1/2}(2-p)(4-p)}$$

Forming ratios of these dosages, we have

$$\frac{D_{\ell}, X}{D_c, X} = \frac{4-p}{2} \quad \text{(a)}$$

$$\frac{D_w, X}{D_c, X} = \frac{X}{w} \left[1 - \left(1 - \frac{w}{X}\right)^{\frac{4-p}{2}} \right] \quad \text{(b)} \qquad (6)$$

$$\frac{D_w, X}{D_{\ell}, X} = \frac{2}{4-p}\, \frac{D_w, X}{D_c, X} \quad \text{(c)}$$

Equations (6) are of particular interest since we wish to know the comparative dosages. Equations (6a) and (6b) are shown graphically for three values of p in Figure 2, where the total dosages from a line source and banded sources of varying downwind widths w are compared with the total dosage from a uniformly distributed source covering the entire distance of interest, X.

Inspection of Figure 2 shows that the maximum total dosage is associated with the line source and this dosage is 10 to 15 percent higher than the uniform source case. The total dosage from the banded source area is intermediate between the line and uniform sources and tends to the latter as the fraction of the distance of interest occupied by the banded source increases (w/X → 1.0.)

If one can ignore for the moment all other requirements that must be met in planning the distribution of sources of atmospheric pollutants in urban areas, the ramifications of Figures 1 and 2 are

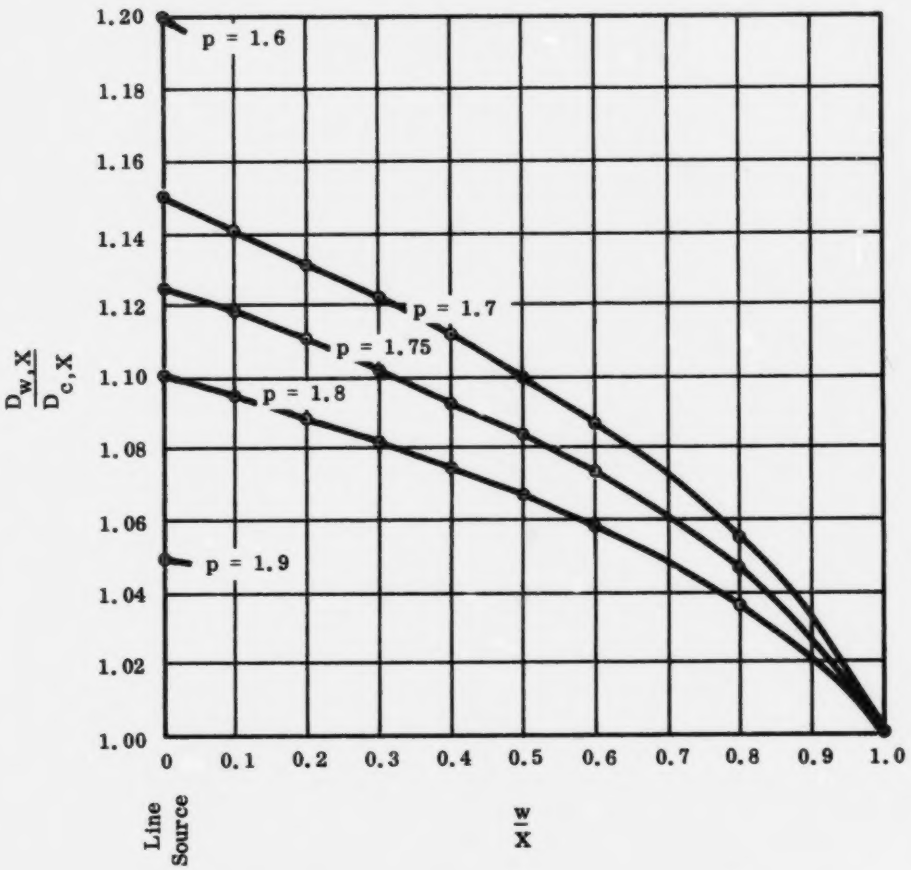

Figure 2. The effect of downwind source width, w, on total dosage in the plane of maximum concentration and over a distance of interest X, for three values of the diffusion coefficient, p. (w = 0 represents the case of a line source.) (See text for explanation of ratio $D_{w,X}/D_{c,X}$.)

almost self-evident. One can minimize, or at least largely constrain, maximum concentrations and can minimize absolutely dosages over an area of interest by distributing the sources of air pollutants as uniformly as possible over that area. The reduction in total dosage by this device is not large, according to this model, but again the value of a 10 to 15 percent reduction in the general exposure of the area or population to air pollutants must be weighed separately.

Some generality can be introduced in the source distributions assumed above. The more practical problems of urban air pollution do require the recognition of constraints set by aesthetics, land utilization, transportation, power and water supplies, topography, and the like. These source distributions are unique to the locality for which they are derived and must be considered individually, a procedure for which the models developed here are equally useful.

We can consider one further problem that is of real interest in city planning. The question may be phrased, "Of what value are 'green-belts' (non-source areas) in the context of air pollution?" An initial solution to this problem may be obtained by solving the model for an arbitrary arrangement of banded source strips. An example of such a solution is shown in Figure 3, where three source bands are arranged, as shown by the shaded strips, at $0 \leq x \leq 3$ km, $7 \leq x \leq 9$ km and $11 \leq x \leq 16$ km. The resultant concentration distribution is shown by the solid line in the graph; for comparison, the concentration distribution that obtains for a uniformly distributed source configuration is shown as the dashed line (total source strength is conserved in this comparison).

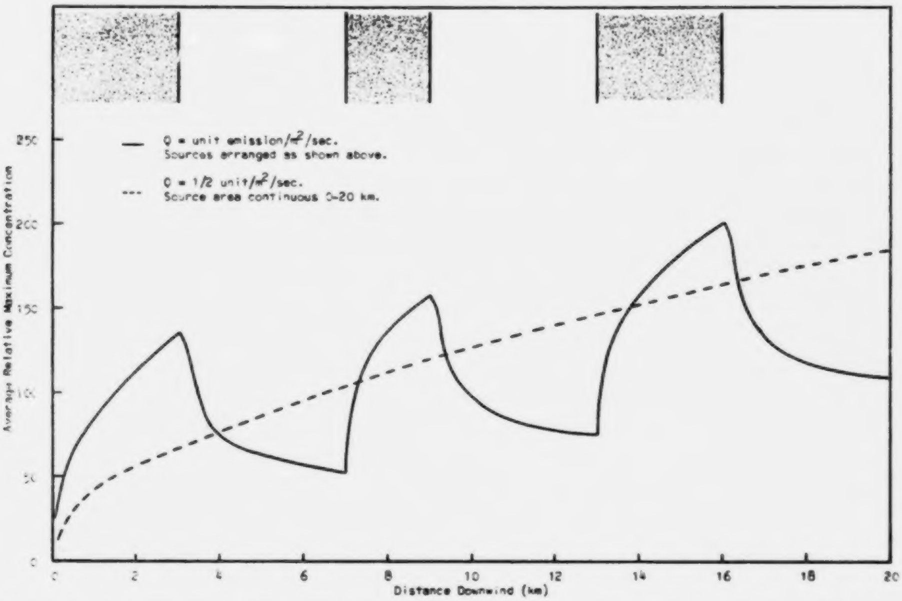

Figure 3. Comparison of maximum concentrations as a function of distance downwind from three arbitrarily arranged banded source areas and the same total source strength distributed uniformly over a distance of 20 km. All source configurations are of infinite crosswind extent.

The comparative excess of concentration (and dosage) in the compressed source strips and the deficit of these quantities in the "green-belts" are obvious from the diagram. Concentrations for these two cases are converging with increasing distance, i. e., at large distances the concentrations and dosages become insensitive to the banded source arrangement.

CONCLUSIONS

The power of mathematical models to cope with the joint effects of source distributions and atmospheric dispersion properties in determining air pollution distributions has been illustrated. The ability of these models to handle much more complex systems of sources and meteorological variability is clearly recognized and requires only the judicious use of available high-speed electronic computer equipment.

A limitation must be recognized, however. These models are no more accurate and complete than the mathematical representations of the physical processes that they incorporate. In the present instance the lack of a thorough knowledge of the vertical exchange capacity of the atmosphere over a rough urban surface and the failure to incorporate loss of pollutants by deposition are most serious areas of ignorance. These must be overcome by continued research; in the meantime we have the mechanism, in these models, to synthesize what we do know in a useful way. Perhaps more importantly, we can use these models as guides to the design of the highly complex experimental programs required to further our knowledge in this important problem area.

Some Aspects of Atmospheric Diffusion in Urban Areas

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Summary

The waffle-type topography of a large city creates two general airflow regimes: a channel flow through streets and among buildings, and an upper airflow. Three types of discharge of pollutants over cities (ground-level, roof-level, and tall-stack discharge) are considered in terms of diffusion by the two airflow regimes. Ground-level discharge is in channel flow, which is principally an aerodynamic phenomenon. Wind-tunnel studies of concentration patterns would be very useful for this source. Roof-level discharge is in a transition regime. A full-scale study would require saturation of an area with sampling equipment for the short duration of a constant wind. A program to develop simulation of turbulence in wind tunnels would prove helpful for studies of roof-level discharge. Tall-stack discharge is in free atmospheric flow, with turbulence generated by ground roughness and by heat from building surfaces. A full-scale study would be required to determine diffusion coefficients over a city.

Gas concentrations in an urban atmosphere may vary over several orders of magnitude. For example, the concentration of SO_2 within the chimney of a coal- or oil-fired heating plant may be of the order of 10^3 ppm, while day-to-day samples taken at street level may be of the order of 10^{-1} ppm or less. In a given atmospheric condition, an observer moving among such sources would not normally experience the highest concentrations. Human beings, animals, plants, and mechanical equipment sensitive to corrosion would be speedily removed from an environment containing 10^2 ppm. SO_2 concentrations of the order of 10^1 ppm are found quite frequently on roof tops, however, and concentrations of 10^0 ppm may be found in upper-story apartments when the wind is in the right (or wrong) direction. At a distance from a given chimney great enough that the contribution of that chimney to the concentration level is negligible, the observer experiences low concentrations of the order of 10^{-1} ppm. These concentrations do not vary rapidly with location. They are caused by the integrated effect of all sources in the area.

Between the recognizable regions of high local concentration and low diffuse concentration, there exists a poorly defined region of intermediate concentrations. This is the ordinary environment of the urban dweller. It is a three-dimensional space in which the concentrations fluctuate in time, and through which the observer moves during his daily routine. Our understanding of diffusion and our knowledge of pollutant distribution within this intermediate region is practically nil.

A research program designed to evaluate air pollution over cities should take into account the characteristics of these three regions, and methods of observation and analysis should be suitable to each region.

ANALYTICAL METHODS

In the mathematical treatment of atmospheric diffusion a real situation is customarily idealized into a simple mathematical model. A tall chimney may be represented by a continuous point source. A multitude of small chimneys dispersed over a large area may be represented by a continuous area source. When these idealizations are made, it is implied, but not always stated, that the derived formulas for ground concentration are valid only beyond a loosely defined distance at which emission irregularities cease to influence the concentration distribution in the plume.

For the isolated chimney the irregularity may appear as an initial plume expansion, which becomes insignificant in comparison with subsequent diffusion after a short travel distance. Since the plume rarely reaches a receptor on the ground in this distance, the foregoing limitation is not a handicap. In a multiple-chimney problem the area-source solution will be valid beyond some distance from the edge of the area. When the principal receptors are among the chimneys within the area, the area-source solution is not adequate.

In a region of multiple sources the technique of distributing the total effluent uniformly over the total area must lead to an underestimate of the maximum concentration experienced by a receptor moving within the area. Diffusion theory generally predicts that all sources upwind of a point will contribute to the concentration at that point. Maximum contributions will come from sources directly upwind. The contributions from sources displaced laterally from the upwind axis decrease exponentially with lateral distance. Practically, the entire contribution will be made by sources lying within a wedge having its apex at the receptor and its body symetrically disposed about the upwind axis. In the mathematical process of transforming the multiple sources into an area source, some of the contaminant is removed from this wedge and distributed over the area outside the wedge. The removed portion makes no contribution to the concentration at the receptor; this results in a lower estimate of the integrated effect than would be obtained if the sources within the wedge were not distributed. Moreover, a receptor immediately downwind of a stack would receive very high peak concentrations.

To overcome this defect one might replace the continuous area source by small area sources of high concentration at the actual chimney locations. Concentrations in the plumes for each chimney might be calculated, and the total concentration at any point would be derived by a numerical summation of concentrations from all sources. This approach would be quite feasible if the physical reality consisted of isolated chimneys rising from level ground of low uniform roughness. In such a case, the mean wind speed and direction and diffusion coefficients could be postulated.

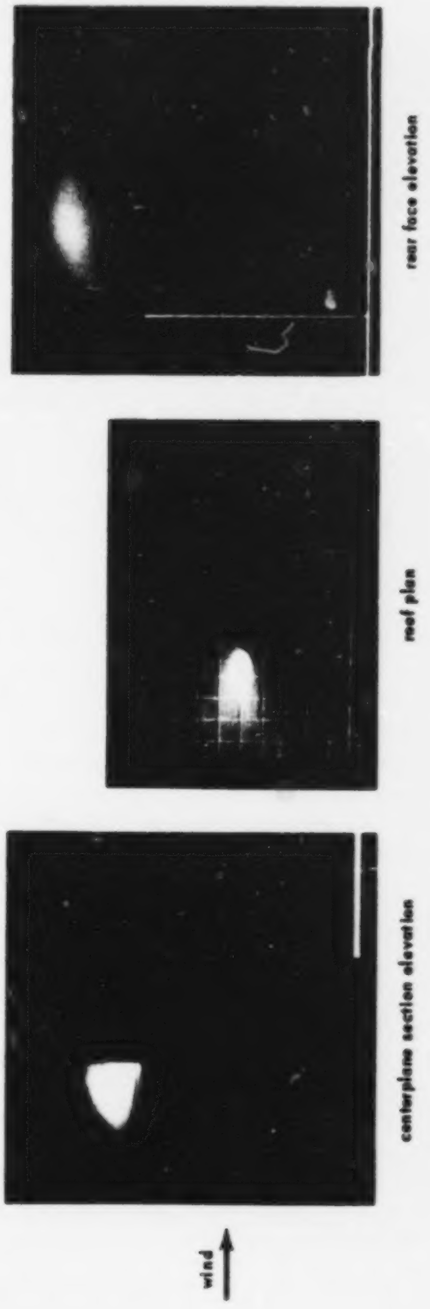
In a city, however, most chimneys do not extend more than a few feet above the roofs of the buildings they serve, and other sources such as automobile exhausts move about on the ground. The mean wind high above the city need bear no simple relationship in speed or direction to the wind at roof or street level. Diffusion coefficients at roof and street level are simply not known. Thus, it is unlikely that a purely analytical approach will prove effective within a city. Experimental data are needed to give clues to diffusion rates in circumstances where the principal factor is the influence of local topography.

EXPERIMENTAL METHODS

How shall such experiments be conducted? Evidently we must consider source location, receptor location, building shape, wind speed, wind direction, and thermal gradients. It is a huge task to instrument one full-size building to cover all possible receptor locations and to conduct such a test during the short time period during which atmospheric conditions remain constant. Moreover, we must consider whether the information obtained in this one test is valuable enough to justify the expense. Generally, such considerations militate against the experiment.

The alternatives to a full-scale field test are spot checks at a given installation or comprehensive tests on a scale model. Recent model tests at New York University found that spot checks are often misleading because neither the instantaneous nor the mean plumes from a source close to a building can be predicted with certainty. One cannot tell whether the spot measurement is a maximum or not. Under controlled wind-tunnel conditions, exhaustive studies of concentration distributions can be made at reasonable cost. Such intensive studies have been performed recently with a model of the Clinical Center of the National Institutes of Health at Bethesda.[1, 2]

Figures 1 and 2 are representative of the smoke pattern photographs made during tests of smoke patterns around single



centerplane section elevation

roof plan

rear face elevation

Figure 1. Smoke Concentrations Around a Cube 0° Orientation

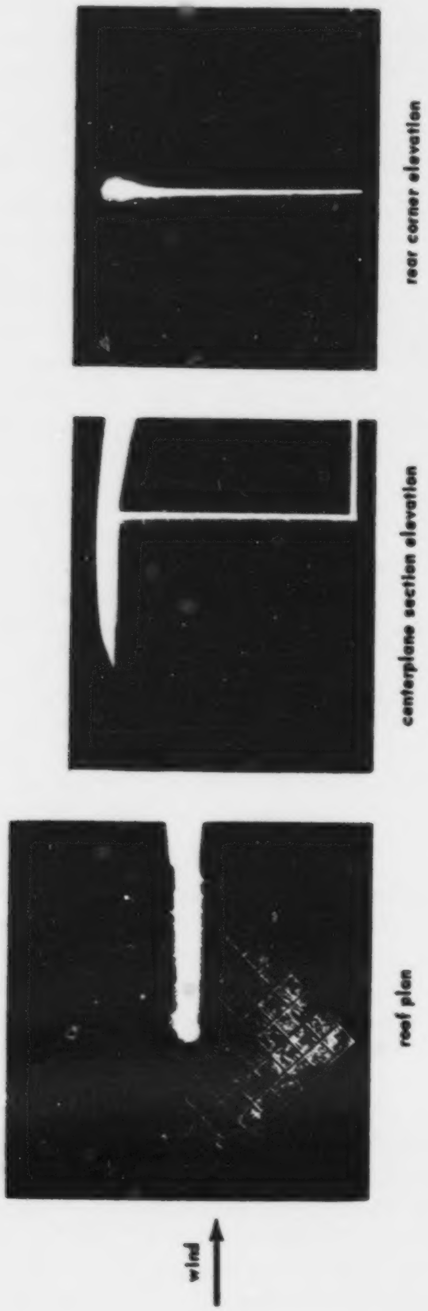

rear corner elevation
centerplane section elevation
roof plan
wind

Figure 2. Smoke Concentrations Around a Cube 45° Orientation

block shapes.[3] They indicate that the maximum concentrations may occur in unexpected locations. For example Figure 1 shows that when a building is oriented with one face normal to the wind, the emission from a flush roof exhaust will produce maximum roof surface concentrations upwind of the exhaust opening. This condition does not obtain in a corner orientation, as shown in Figure 2.

AN URBAN AREA DIFFUSION RESEARCH PROGRAM

In evaluation of pollution over and within an urban area, some generalizations of source distribution are needed to establish typical pollution patterns. Three major source groupings can be established. The first contains the very tall chimneys found on power plants, refineries, and municipal incinerators. The second contains the numerous heating plant and incinerator exhausts at roof level of the older five- and six-story buildings that fill our city blocks. The third group contains the automotive exhausts at street level.

None of these source groupings are amenable to strict analytical treatment. The tall stacks may be considered as elevated continuous point sources, but there is a dearth of information regarding diffusion coefficients over urban areas. The roof-top emissions may be treated as rectangular area sources separated by clear bands formed by streets and avenues, but it is difficult to predict how rapidly the gases will penetrate downward between buildings. Diffusion from ground-level sources is greatly affected by the channeling of air currents between buildings and the back flow in eddies created by building corners; analytical methods are completely inadequate for this type of source.

Since it is generally desirable to use analytical methods where possible, experiments should be performed to determine diffusion coefficients and mean wind profiles at various elevations above roof level. These quantities should be measured at full-scale in the atmosphere. Although the controlled environment of the wind tunnel makes testing easier, the modeling of atmospheric turbulence in the wind tunnel has not been developed sufficiently to give reliable results, especially where thermal gradients are involved. There is a possibility that wind tunnel models may be used to determine diffusion coefficients near roof level under neutral conditions and high wind speeds, since the mechanical turbulence in this region should be much greater than thermal turbulence. Until the scaling of turbulence spectra has been more fully explored, however, this approach can not be recommended.

Once the diffusion coefficients above the city have been determined, the analysis of tall stack sources may proceed. If the coefficients are found to vary considerably with height, it may be necessary to refine the diffusion formulas to permit arbitrary variation of wind speed and diffusion coefficient. Numerical methods may be useful to give approximate but practical solutions. One open question is the elevation of the effective ground. Since ground concentrations theoretically vary inversely as the square of the source height, the assumed ground elevation is important. Perhaps the source height ought to be measured from the z_0 of the large-scale wind profile over the city.

The rooftop area source poses an interesting analytical problem, since part of the pollutant will diffuse upward and part downward into the space between buildings. This aspect is beyond my competence and I leave it as a challenge to the analysts. Rooftop diffusion downward into city streets can easily be measured in model tests, however. A representative section of the city containing several typical repetitive block arrangements can be tested for area emission or multiple-point-source emissions on a given roof. Three-dimensional concentration gradients within the street channels can be measured as far downwind as is necessary for the concentrations to reduce to negligible values. A numerical addition of displaced concentration patterns will give the integrated effect of emissions on all buildings.

The diffusion of pollutants from street-level sources should be studied with models to determine the three-dimensional diffusion pattern. Visual smoke studies to determine the region of highest concentration, followed by quantitative concentration measurements in this region offer assurance that the maximum concentrations will be detected. Model concentrations can be represented as non-dimensional coefficients, which may then be used with full-size values of wind speed, source strength, and building size to obtain full-size concentrations.[3]

The validity of model testing of diffusion around buildings has not been established as yet by direct comparison of full-scale and model experiments in a variety of turbulence conditions. There is theoretical support and some experimental evidence to indicate that the procedure is valid for neutral atmospheres and higher winds. Tests of gas bomb releases in a mock-up of a full-scale village and a model of the village in a wind tunnel have shown good correlation.[4, 5] Funds have been requested from NIH for comparative tests to establish with greater refinement the degree of discrepancy between model and full-scale tests in the case of diffusion around a simple block-shaped building, and, if such discrepancies are found to be large, to develop analytical or experimental techniques to improve correspondence.*

The three-mode source arrangement suggested in the previous paragraphs is, of course, an approximation. Even if all the analytical and experimental procedures that were discussed should prove effective, there is no assurance that the combined picture would correspond to reality. Some experimental evidence must be found against which the predictions can be weighed. There is no substitute for full-scale field sampling for this purpose.

A study just beginning in New York City may provide the type of information required. The New York City Health Research Council has given a research grant to Cornell University to correlate weather and pollution variables with the incidence of pulmonary ailments in a normally healthy population. The portion of the program concerned with weather and pollution documentation has been subcontracted to New York University under the direction of Dr. Wm. T. Ingram. I am involved in setting up the weather and sampling stations. The medical and statistical analyses will be handled by Cornell.

We intend to record continuously the concentrations of a number of atmospheric pollutants at four levels of a 200-foot-high building that stands fairly isolated in a more or less uniform area of 5-story tenements. In addition to the contaminants, we will measure the wind speed at the roof, the variation of temperature with height, solar radiation, rainfall, mean temperature, and pressure. We also intend to measure simultaneously, under selected test conditions, the horizontal variation of specific pollutants. To supplement our own measurements, the records of the various weather stations at municipal airports and stations of the New York City Department of Air Pollution Control will be used.

It is hoped that the data collected in this manner can be integrated into a space-time picture of the pollution distribution in the area under consideration, which measures about 1 by 5 miles and is located on the west shore of the East River in midtown Manhattan. This information will then be analyzed in conjunction with records of the activity of sample populations in the area and their state of health. Fortunately, this information will also be available for other studies, such as those suggested in this paper.

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*The NIH has awarded Mr. Halitsky a 3-year research grant for this purpose, effective June 1, 1962.

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DISCUSSION

FROM THE FLOOR: We frequently run into the problem of an adequate sampling population. You mentioned using Welfare Department cases. Are we to assume that everybody in Manhattan is on welfare?

MR. HALITSKY: The sample population was selected by Cornell. It consists principally of Welfare Department cases, who report weekly for their allowances and may thus be questioned about their ailments. Some volunteers not on welfare are included. Our building choice was based on physical suitability and proximity to the center of the sample population. The economic status of the population will have to be filtered out statistically.

MR. SMITH: Do you have any data at all from the Clinical Center at Bethesda to correlate with the concentration measurements you made in the tunnel? This is the kind of thing I think would be most instructive.

MR. HALITSKY: There are no field-correlation measurements available. I wish I could assure everybody that the tunnel measurements can be converted to field concentrations simply by inserting the appropriate known parameters into the scaling formula. In tests of this type, where flow disturbances are aerodynamic rather than thermal in origin, there are indications that diffusion is determined mostly by turbulence induced by the building rather than turbulence in the approaching air stream. The request for research support from NIH is aimed at resolving this problem.

SYMPOSIUM: AIR OVER CITIES

MR. SMITH: To finish my question, I think you are right that in such cases the tunnel probably represents beautifully what happens around a building. But I think that many of us are a little worried about the scale-factor problem, about whether the model representation is correct or not.

MR. HALITSKY: My tests were limited to regions very close to the buildings because I, too, am concerned with the increasing influence of atmospheric turbulence as wake turbulence decreases. I don't think there is any information available on the relative importance of atmospheric turbulence in the presence of wake turbulence.

MR. COLLINS: For a good many years I worked with an industrial concern that took advantage of some of the fine work that Mr. Halitsky and his colleagues are doing at New York University. I would like to tell a little story and then ask him a question.

We were consulted on the design of a chemical laboratory, which had stacks for many chemical exhausts on the roof. The question arose as to how high these stacks should be to prevent the recirculation that Mr. Halitsky has demonstrated. After studying some of the shapes in the wind tunnel, we decided that if the stack were well above the surface of separation there should be no trouble.

We passed our recommendations on to the design engineer and the architect. We didn't hear anything more about it until about a year later. The laboratory had been built at that time, and we got an emergency call that about twice a week they had to evacuate all the personnel, 250 people, because of recirculation of H_2S and other unpleasant fumes.

We went out to look at the laboratory, and this is what had happened. True enough they put the stacks up to the height of 30 feet above the roof as we had suggested. But the architect didn't like the looks of them. He built a penthouse around the stacks so that the actual stack was about six inches above the roof of the penthouse; furthermore, the penthouse had a 2-foot papapet on it, and all the fumes were trapped in this little well on the top of the building and they just sort of oozed out into the air intake.

My question is, how do you win an argument with an architect?

MR. HALITSKY: Well, actually it is pretty tough. In the Bethesda work we tested not only the original conditions, but some suggestions that had been made for alleviating the conditions. There were severe restrictions on what could be done with the building, because aesthetically they are very proud of it. I think this is true in many of the modern types of construction.

FROM THE AUDIENCE: Your use of this simple model for data reduction and inclusion of V in the determination of scale factor seems to imply that there is a stationary wake form with respect to wind velocity. Is this in fact so?

MR. HALITSKY: This is so if you use the term quasi-stationary instead of stationary to indicate a time mean rather than an instantaneous wake form. We have tested a number of sharp-edged building models at different tunnel wind speeds varying from 1 to about 15 ft/sec. The values of K in the wake do not vary with wind speed above a speed of about 3 ft/sec. I believe that this is due to the sharp edges of the building, which prescribe the wake shape. A rounded building shape would have a wake that is more sensitive to boundary layer formation, which in turn depends on Reynolds Number and therefore on wind speed.

MR. MOOK: On the matter of scaling, I think the same phenomenon of exhaust recirculation occurs when the wake is not generated by a moving wind but by a moving building or car.

MR. HALITSKY: Yes. I have a station wagon with the rear seat facing backward. My children like to ride in the back with the rear window open. The exhaust recirculates into the rear window, and out through the butterfly in my left front window. It is not so bad on a level road with the throttle open, but when going down hill while braking, I find the exhaust concentrations up front intolerable. As a general rule, I do not permit the rear window to be open more than 3 inches from the top.

FROM THE AUDIENCE: In your tests, to what height above the building did you have to go to measure the free wind speed?

MR. HALITSKY: The height varies with the distance downwind from the leading edge. On the cube the height of the wake at the downwind edge of the roof is about half the height of the cube. The speed just outside of the wake is about 15 to 20% higher than the free wind speed.

FROM THE AUDIENCE: In other words, if we were making a measurement for air pollution purposes, we ought to get up a distance of half the height of the building?

MR. HALITSKY: It depends on wind direction. The wake over the roof in a cornering wind is very small. The wake in a frontal wind is large. To be absolutely safe in all wind directions you would have to get above the largest wake, and even then you must take into account a certain degree of overspeed. This figure of half the building height applies only to a cube. I believe a tall building of small plan cross section would have a wake over the roof no larger than that of a cube of side area equal to the plan area of the building.

MR. GOLDSTON: In reviewing the papers that have been presented here in the past day and a half, I hope I leave here more enlightened than confused. I can see the immensity of the problems we face here, and their complexity. I think we are facing a problem of greater gravity than simply that of time and space, per se. I just wonder whether, at some time in the future, we would be able to take the mass of material that we have considered here, the heat, the various strata and layers of pollutants, the precipitation patterns in cities, the suburban temperature variations, and make them amenable to a simple statement that we could use as a guide to further our activities and studies.

MR. HALITSKY: I think that other members of the Symposium would be better qualified to answer that question.

DR. HILST: Throughout what we have been talking about this morning there seems to run a theme not stated, and I hope it is not assumed, that there are unique solutions to the problem which we face. I would like to disabuse anybody with that idea. We recognize that we are working with highly variable fluid quantities here. They vary with time and with space. We recognize that, from a statistical point of view, if we are going to define over a large amount of time, we have to take a large sample. But we also recognize that the atmosphere itself is guilty of taking small samples. It has a large degree of freedom within which to work and because of inhomogeneity and the rapid changes in the wind and temperature, the atmosphere itself gets only a small chance to act in the specific circumstances we prescribe. There is no solution; we can only describe the distribution of possible solutions.

CHAIRMAN NEIBERGER: I think that we can all see that there are various approaches to this problem of dispersion in the atmosphere. The approach of the statistical turbulence measurements, the approach of the continuous diffusion concept, and the approach of the model experiments; the use of computers both analog and digital give some hope of solving the complex problems.

Session 3: Present and Future Needs for Meteorological and Air Quality Observations

J. J. SCHUENEMAN,* *Chairman*

The Relative Importance of Some Meteorological Factors in Urban Air Pollution

ELMER ROBINSON, *Stanford Research Institute*

Summary

Wind patterns and inversion or stability conditions are important meteorological factors affecting urban air pollution. Popular attention is usually focused on inversion, even though wind conditions can be shown to be more significant in many situations. The relative importance of winds and inversions is examined in terms of theoretical, statistical, and climatological considerations.

This discussion is not a technical paper in the usual sense, since it puts forth a particular point of view of the author and does not include the examples of contrary fact or opinion that would be necessary in a technical paper. Neither does the discussion include a comprehensive presentation of available research studies. This type of presentation was specifically designed to take advantage of the program chairman's remark that "controversial topics should not be avoided." The author hopes that this approach will lead to a more careful appraisal of urban diffusion meteorology.

Not long ago an eastern city experienced a period of particularly severe air pollution. When a newspaper reporter asked the cause, he was told that the pollution was due to a temperature inversion affecting the area. On the West Coast it sometimes seems that everyone believes that if there were no inversion over Los Angeles there would be no smog in that afflicted area.

Although public recognition of the smog-producing effect of a temperature inversion seems quite remarkable, careful consideration indicates a rather poor public understanding of urban air pollution meteorology. The most unfortunate aspect of this situation is that professional meteorologists are doubtlessly to blame for this state of affairs. The inversion is often given special treatment and emphasis, and the rest of the meteorology is all too often glossed over or not mentioned at all. With respect to meteorological air pollution factors, it would appear that a much better case can be made for a weak wind pattern than for a low inversion. In the following discussion the relative importance of these two parameters, inversion and wind, will be considered in some urban air pollution situations. The impact on air pollution meteorology of "inversionless" thinking will be examined, and a more rational approach to an explanation of city-wide air pollution will be outlined.

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AREA-WIDE CALCULATIONS

An exercise undertaken at some time by almost everyone in air pollution is the calculation of a typical volume of air available for the dilution of an area's daily emission of pollution. Table 1 shows the results of such calculations for the San Francisco Bay area. On the first line are the calculated concentration figures for two inversion heights with typical nonsmog day winds.

TABLE 1

CALCULATED AREA SO_2 CONCENTRATIONS
San Francisco Bay Area (500 mi^2)
SO_2 emissions = 1147 T/day

Ventilation Rate	Inversion Height	
	1500 ft.	1000 ft
8 mph	0.07 ppm SO_2	0.11 ppm SO_2
5 mph	0.11	0.17
2 mph	0.29	0.43

(Ref: Wohlers, Community Air Pollution Sources)

The succeeding lines of calculations show the results of altering the meteorological parameters in ways that are typical of moderate and severe air pollution days. When the inversion is lowered to a moderate level with constant winds, the result is a proportional but moderate increase in concentration. When the inversion is left at its average height and the average wind is dropped to 2 mph, the resulting calculated concentration change is still proportionate but it is obviously much more pronounced than in the inversion change. In the low-inversion, low-wind situation the wind is still the dominant feature. It is generally much more realistic to expect a several-fold change in wind speed than in inversion height.

When the day's smog story is written, however, it will probably begin with: "A strong inversion layer sealed off the area today and smog concentrations quickly climbed to irritation levels." Perhaps the wind pattern will be mentioned, perhaps not.

STATISTICAL RELATIONSHIPS

Another way of viewing the inversion and wind relationship is to correlate their values with air pollution measurements. This has been done many times and perhaps it is dangerous to present individual examples; however, since the object of this discussion is to look for over-emphasized inversions, some selection is perhaps excusable. In the Los Angeles air pollution situation, the temperature inversion has probably received its earliest and widest attention. Thus a more careful look at some of the relations among inversions, wind, and smog in Los Angeles may provide a valuable example.

It should be pointed out that the Los Angeles inversion is primarily a subsidence inversion associated with the subtropical Pacific High. The height of the base averages between 1000 and 1500 feet during the summer and fall months. The inversion base is below 3000 feet for 80 to 90 percent of the time from June through October. Below the inversion base, thermal turbulence will be a dominant factor in mixing emissions. The air below the inversion is usually identified with the on-shore movement of marine air, while the air above the inversion is dry superior air.

A number of years ago Stanford Research Institute correlated oxidant data with various meteorological variables. These factors included the afternoon height of the inversion base and the daily wind movement in the Los Angeles area. Both simple and partial correlation coefficients were calculated on the basis of data for the period of July 1 to November 30, 1952. The results are shown in Table 2.

TABLE 2

CORRELATION COEFFICIENTS FOR LOS ANGELES
(July 1-November 30, 1952)

Relationship-1 PM Observations	Single Correlation Coefficient	Partial Correlation Coefficient
Oxidant--Wind Speed (m = 130)	-0.70	-0.41
Oxidant--Inversion Height (m = 130)	-0.67	-0.29

The simple correlation coefficients between total oxidant and either wind speed or inversion height were high. The negative result is expected with both variables. The partial correlations do not show the same picture, however, and the correlation for oxidant and wind speed is higher than that for oxidant and inversion height. Other calculations have shown that in Los Angeles there is a strong correlation between inversion height and wind, and thus it is necessary to use partial correlations to separate this interrelationship.

Correlations such as these were carried out several times with Los Angeles observational records for various periods. The results in general showed less correlation between inversions and smog than was shown here. Thus it seems that the subsidence inversion is not as significant a factor in the Los Angeles smog picture as many writers have claimed.

URBAN CLIMATOLOGICAL CONDITIONS

The statement has already been made that for diffusion of urban pollution the effects of wind movement are more important than are the effects of inversion. One apparent explanation for the lesser role of the inversion is the heat island produced by the city itself. This phenomenon would produce less stable surface conditions within the city without its being apparent at the usual neighboring airport observation point.

This factor of urban climate has been carefully studied by Duckworth and Sandberg (Figure 1). Their study showed not only that large temperature gradients occurred at night between open and urban areas but also that this temperature effect frequently caused instability up to about 3 times the roof height. The study also related the magnitude of this heating effect to the size of the city: the more developed the city, the more it modified its

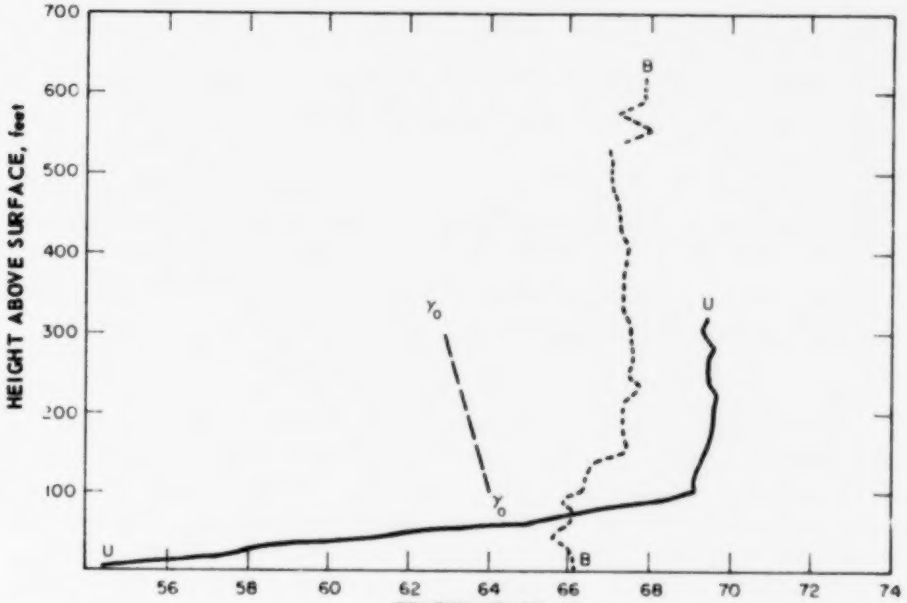

Figure 1. San Francisco wiresonde data for 2210 PST, 26 March 1952, showing soundings over built-up (B) and adjacent undeveloped (U) areas.

atmosphere; thus the larger the city, the less likely it is to have surface inversion conditions.

The impact of this urban heating effect on pollution diffusion seems quite clear. The polluted layers are unstable during the day because of the solar heating of the buildings and pavement areas, and at night the heat lost by these surfaces is enough to prevent strong stable conditions from building up. There is probably not much change in the stability conditions over the central urban areas. Thus it is not surprising that pollutant concentrations are not highly responsive to stability parameters such as inversion height or inversion conditions measured outside the central area.

INTER-CITY COMPARISONS

Another way to consider these urban diffusion factors is to compare similar pollution data from several different cities. Data for three California areas are shown in Figure 2: Berkeley is in the San Francisco Bay Area, Los Angeles is in the Southern California Los Angeles basin, and Riverside is 50 miles inland from the Los Angeles basin. The pollutant shown in these data is the daily oxidant maximum concentration for 1960.

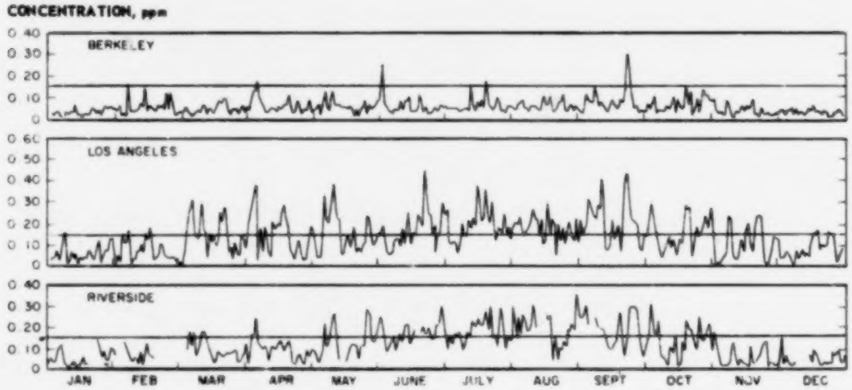

Figure 2. Daily maximum oxidant concentrations in three California cities, 1960 (potassium iodide method).

If the potential air pollution hazard can be judged from the yearly maximum value of oxidant, these areas did not differ greatly in 1960: the maximum value in Berkeley was 0.30; in Los Angeles, 0.45; and in Riverside, 0.37. The frequency of the high concentration days, however, is considerably different for the three areas. High values, though rare in Berkeley, were the general thing in Los Angeles except for the winter months, and were the normal situation in Riverside during the summer and fall.

This pattern is not explained by the inversion conditions, because there is very little difference between those in Los Angeles and in Berkeley. An important factor that does differ is the wind. Berkeley has considerably more wind than either Los Angeles or Riverside, and the wind is normally strongest in midsummer. When the wind blows, Berkeley has little pollutant accumulation as shown by the data; on the few days when the wind does not blow the pollutant peaks can occur.

A comparison of the Los Angeles and Riverside data indicates the ineffectiveness of thermal mixing as an important factor in establishing community pollution levels. Riverside is in an area that regularly is considerably warmer than Los Angeles. This warmer temperature causes the inversion base to rise rapidly during the day and to exceed that reached by the inversion over Los Angeles. Although it is difficult to compare pollution values without studying the source areas, the data at hand still might be appraised in the following manner: (a) Since the development in Riverside is less than in Los Angeles, lower pollution levels would be expected; (b) if increased thermal turbulence were a major additional factor reducing pollution levels at Riverside, concentrations should be significantly lower than in Los Angeles; (c) since concentrations are not markedly lower, it seems doubtful that much reduction in air concentration values can be attributed to the midday inversion height.

DISCUSSION AND CONCLUSIONS

Several aspects of the stability-wind situation have been described. First, pollutant concentrations were shown to be better related to wind conditions than to inversion conditions; second, it was pointed out that wind conditions normally vary over a wider range than stability conditions; and third, it was shown that the city itself is the cause of prevailing unstable conditions in the polluted air. In spite of facts such as these, the idea is still prevalent that pollution problems go hand-in-hand with inversion conditions.

The Public Health Service - Weather Bureau meteorologists have made a valuable step in the proper direction with their large-area air pollution studies. In these studies they have pointed out that a stagnating anticyclone is the basic characteristic of large-scale urban pollution incidents. The stagnating High brings to an area both a weak wind pattern and low-level stability. The preceding discussion has tried to make the point that the wind pattern is more important than the stability. Perhaps it would be even more logical to argue that since a stagnating anticyclone is the basic meteorological cause of air pollution troubles, then air pollution meteorology should deal primarily with this weather system rather than with various individual or local wind and inversion conditions. The Public Health Service studies take this more inclusive type of approach. It is to be hoped that their results will have the needed impact on air pollution thinking.

It seems clear that air pollution meteorologists have been caught in a trap caused by the popular nature of air pollution troubles. In an effort to supply meteorological explanations to a large nontechnical audience, a "popular" description of the weather factors was provided. A semi-mysterious warm air layer, called an inversion, was a more interesting concept to present to the public than either the prevailing winds or the stagnating anticyclone. Once the description was provided, it reproduced itself many times, and repetition made it "authentic." Progress toward public understanding of air pollution meteorology depends upon how rapidly this popularized erroneous description can be replaced with real definitions.

DISCUSSION

MR. FIELD: I was just curious. How many stations do you use when you arrive at an oxidant figure for the city of Los Angeles? And when you say maximum concentration, is that an average or the peak reached during the day?

MR. ROBINSON: These data were the peak values attained by a recording instrument situated in downtown Los Angeles. This is not necessarily an average value for the City of Los Angeles, which would be more difficult to realize. These data are probably representative of rather large areas within the city.

MR. FIELD: Well, I am curious. How do you select the station? Is it simply put there because it is there?

MR. ROBINSON: Mr. Kauper has probably had more to do with selecting the stations than anybody else here. All I did was select the data.

MR. KAUPER: That was his first mistake.

I hope I am the reverse of the architect. We advise where stations go, and then architect types choose stations. It depends where there is space available, within rather broad limits. In this case, I think that our downtown Los Angeles station has varied from the top of our present building, which is in skid row, six floors up, to the middle of town, considered as Pershing

Square, sitting within a bunch of banana trees, and directly over a rather large parking lot. The resulting oxidant values at these various locations have varied considerably. Not because the instrument was changed, but because the environment was changed. At the time of this work, in 1960, the station was on the 6th floor, in a rundown section of town, and slightly east of the main traffic area.

MR. FIELD: I am just wondering how you can compare values from three different stations if they are set up without any regard to conditions you are trying to measure. I am sure if you set up three stations in one city, you will get three different variations.

MR. KAUPER: That is what we have now.

DR. NEIBERGER: How many do you have now?

MR. KAUPER: I haven't looked lately but there are probably about seven -- not in the city, but in the county area. They range from extreme west to east, and as a rule the oxidant values seem to come out higher in the direction toward Riverside and lower toward the coast. As a matter of fact, our downtown Los Angeles readings are relatively lower than those in the eastern suburbs region.

MR. ROBINSON: I did not put the data for Anaheim in here because I didn't want to get into the argument as to how much Disneyland might have done to the oxidant, but the data did show that with the eastward transport of the marine air, it continued to develop higher oxidant concentrations.

MR. HOLZWORTH: I think these data you showed were from the publication by the State Department of Public Health.

MR. ROBINSON: Yes.

MR. HOLZWORTH: Having been with them for a time, I am somewhat familiar with their selection of these data. In order to make as much data available as possible and at the same time to cover as much territory of the state as possible, they include one station for each county. They give consideration to the continuity of the data, the reliability of the data from each station (such as breakdown of the instruments, and so on), and to the representativeness of the stations. For instance at Riverside County there is more than one instrument, but they chose one and they hope that that station will remain in the same place for a long time to come, so that they will have a long comparative record.

DR. NEIBERGER: First, I wanted to say something about inversions and then I want to ask something about Riverside.

The role of the inversion is obviously a necessary one, even though it isn't a sufficient one. That is shown by the fact that even though you get the advection of the air from Los Angeles over in the desert very often, somehow or other you never get eye irritation. The same air manages to mix to still higher levels. So I don't think that you can belittle the inversion; it is a necessary part of the picture. The fact that winds are important I think has been recognized. I don't know at whom the criticism was aimed, but I was among the first to have written on this subject, about 15 years ago. In a little bit earlier work Leopold and Veer, who, as far as I know, gave the first study of air pollution in Los Angeles, mention the inversion and then devote most of their paper (in the transactions for the AGU for 1945) to the wind patterns over Los Angeles.

So I think it has been recognized all the time that this volume of air through which the pollution can go is a function of these factors: the horizontal dispersion due to the wind, the vertical dispersion due to the wind, and the limitation to vertical dispersion due to the inversion. And I remember many times we said that the only reason they didn't have this type of smog at all in those days in San Francisco was that they have twice as much wind as we do.

But I wanted to ask what specifically you had in mind about Riverside, because we have at various times examined the trajectories of the air and the behavior of the oxidant as it moves along from the west coast. At this time of year when we get drifts towards the coast the worst situation is out in the western part of the area. But ordinarily, in most of the smog, we follow it from the west coast, where there is practically zero oxidant, (8 or 9 ppm maximum) into the downtown area, where you get 20 to 30 ppm, then to Pasadena, where it might be 30 to 40 ppm, and then continuing all the way through to the late afternoon, when the peak value is reached at Riverside. And the fact is that most of the time, even though the inversion just about gets wiped out at Riverside, the maximum is still reached there.

I was wondering what type of study you had in mind at Riverside.

MR. ROBINSON: The point that I was trying to make on that Riverside-Los Angeles comparison was that if you take the surface temperatures and extrapolate them against the upper air soundings you get an increased depth of turbulence, an increased depth of mixing as the trajectory moves inland. In some of my own thinking, perhaps, this has tended to play a more important role than more careful consideration might have placed on it. This thermal turbulence, which I think is a factor in the Central

Valley of California -- in Sacramento and Stockton -- is almost cutting away at the base of the inversion. Increased turbulence does not seem to be as important a factor in all the air pollution concentrations as one might expect from reading some of the technical writings on urban air pollution studies.

Measurement Programs Required for Evaluation of Man-Made and Natural Contaminants in Urban Areas*

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Summary

Existing studies of diffusion in transitional states emphasize the need for more comprehensive research programs near shorelines, over lakes, over varying terrains, in valleys, within forests, and over and within uncomplicated cities of various sizes. Because of the serious public health problems created by aeroallergens, many more centers are needed for aeroallergen research. Pollen samplers that minimize nonisokinetic sampling errors must be developed. Television towers should be widely instrumented, not only for lapse rates in typical varieties of terrain, but also for contaminant evaluation. Tracer studies are needed to permit direct and accurate determination of diffusion coefficients. Relatively simple methods are required to assess long-term trends of pollution by industrial waste products. Methods of calibrating electrical conductivity measurements in terms of air pollution levels should be devised and used widely.

URGENT PROBLEM AREAS

Diffusion In Uniform And Steady States

It is clearly logical to begin the evaluation of atmospheric diffusion by studying diffusion under the least complex circumstances. For this reason most of the comprehensive investigations undertaken thus far have been confined to the simplest steady-state conditions. Such studies have been made in England[10, 27, 28], in the United States[2, 4, 19], and in the U. S. S. R.[21, 24] for uniform and level terrain and for limited time periods, over which atmospheric conditions were effectively uniform and steady in space and time.

Within cities, however, the presence of buildings and other obstructions to air flow leads to substantially different diffusion patterns. It is unfortunate that virtually no observational data on diffusion within typical cities are available. A beginning should be made by conducting a measurement program of atmospheric

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diffusion with a city under the simplest possible conditions. The city should be one on a flat terrain, without topographic features, with statistical uniformity of building type and size. The study should be conducted near the center of the city, away from edge effects. Appropriate times for the field investigations should also be chosen. The most satisfactory periods of the day will be from 0 to 4 hours and from 12 to 16 hours, and the best meteorological conditions will have wind speed and direction most nearly constant, so that steady-state conditions most nearly prevail. Later studies would be made in succession in cities having increasingly more complex terrain and structural diversity.

Some of the techniques and instrumentation required for such studies will be discussed in later sections.

Diffusion In Transitional States

Most of the existing diffusion theories are based on the assumption that turbulent diffusion is invariant with time and space, a basis that requires exclusion of a wide range of situations that are of the utmost importance in urban air pollution. The atmosphere is a dynamic entity whose diffusional characteristics may and often do change radically within short periods of time. When the field of atmospheric turbulence exhibits marked variations in time or space or both, then the resulting atmospheric diffusion may be referred to as "diffusion in transitional states."

Diffusion in River Valleys - The first investigation of diffusion in transitional states was conducted in the Columbia River Valley near Trail, British Columbia.[16] Two examples were discovered, one associated with a space variation of turbulence and the second with a time variation. The space variation resulted from a dry adiabatic lapse rate in the lower portion of the valley surmounted by an inversion aloft but in the valley. Although turbulence and mixing were pronounced below, high concentrations of SO_2 occurred at the surface because the inversion aloft prevented upward diffusion out of the valley. A similar condition has since been shown to be the primary contributing factor in Los Angeles smog. Containment of pollutants beneath an inversion aloft even when terrain does not limit horizontal mixing has been named "trapping."[1, 15]

The time variation within the Columbia River Valley occurred during the morning hours in summer, when solar heating caused a turbulent layer to develop upward from the surface, replacing an inversion. When this turbulent layer reached the smoke plume aloft, it brought high concentrations of SO_2 to the valley, a process known as "fumigation" caused by "inversion breakup diffusion."[11] Many other examples of this process over flat terrain have since been found.

Diffusion Near Shore Lines - Because of the need for an adequate water supply, river valleys and shore lines are preferred locations for cities and industries. Some of the aspects of the "diffusion in transitional states" in river valleys have been mentioned above, but relatively little research on such diffusion near shore lines has been conducted, although a start has been made.[17, 18]

The construction of nuclear power plants at shore-line locations on the Great Lakes has led to measurement programs that will establish the air pollution climatology of these areas. The authors are engaged in such measurement programs at the Enrico Fermi Atomic Power Plant near Monroe, Michigan, at the west end of Lake Erie and at the Big Rock Point Nuclear Power Plant near Charlevoix, Michigan, on the east side of Lake Michigan. The latter is shown in Figure 1, an aerial photograph showing the plant in the foreground and the 250-foot instrumented meteorological tower behind it, very near the water's edge. Figure 2 shows the steel tower and wooden pole as viewed from the lake. Anemometers and wind vanes are installed at 32 and 64 feet on the pole and at 128 and 256 feet on the tower. Water temperature at 3 feet beneath the lake surface and air temperature at 10, 50, 100, 150, 200, and 250 feet on the tower are measured for lapse-rate determinations. All winds and temperatures are recorded in the small building at the base of the tower.

At a shore line the horizontal distribution of the diffusion field is the important factor. Marked horizontal variations in turbulence may be due to horizontal differences in the temperature of the underlying surface; these temperature differences induce or suppress thermal turbulence. Alternatively, such horizontal variations in turbulence may be due to differences in the roughness of the underlying surface; these differences also can cause mechanical turbulence to increase or to decrease in intensity. At a shore line both surface temperature differences and surface roughness differences may be pronounced and may combine to produce highly complex patterns of diffusion.

Two main types of diffusion in transitional states should be considered: one with the horizontal distribution of turbulence stationary; the second with the horizontal distribution varying with time.

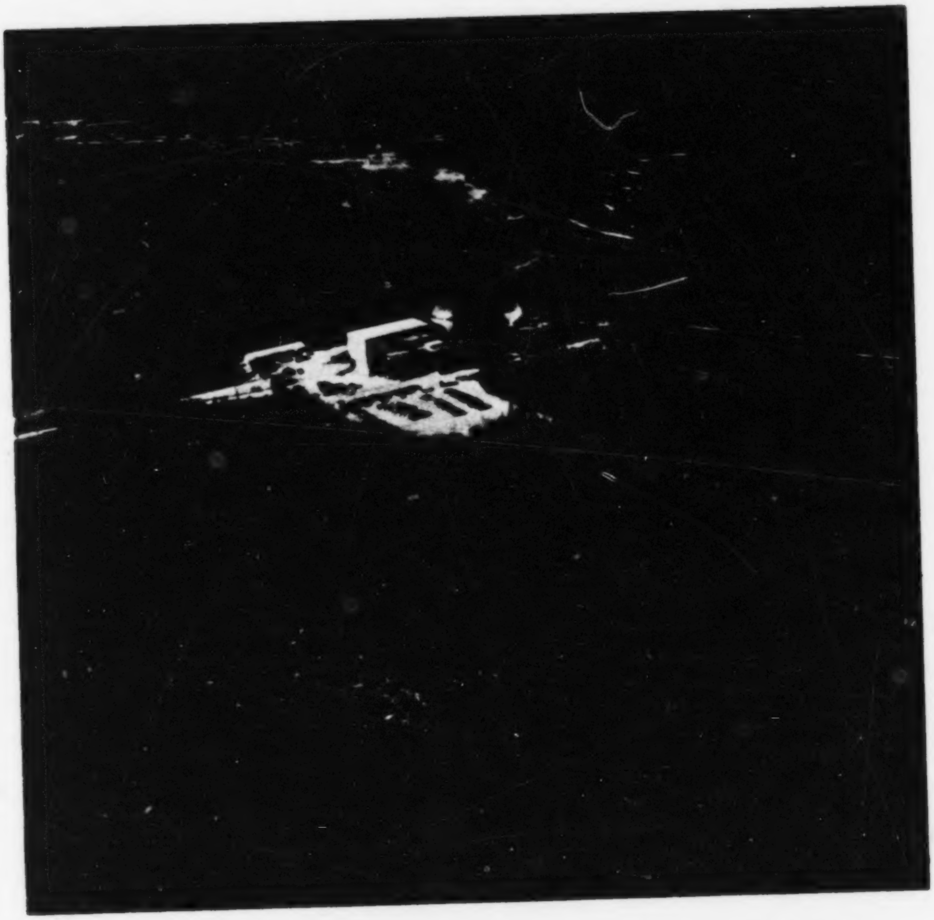

Figure 1. Aerial view of the Big Rock Point Nuclear Power Plant near Charlevoix, Michigan, with 250-foot instrumented meteorological tower near the shore line.

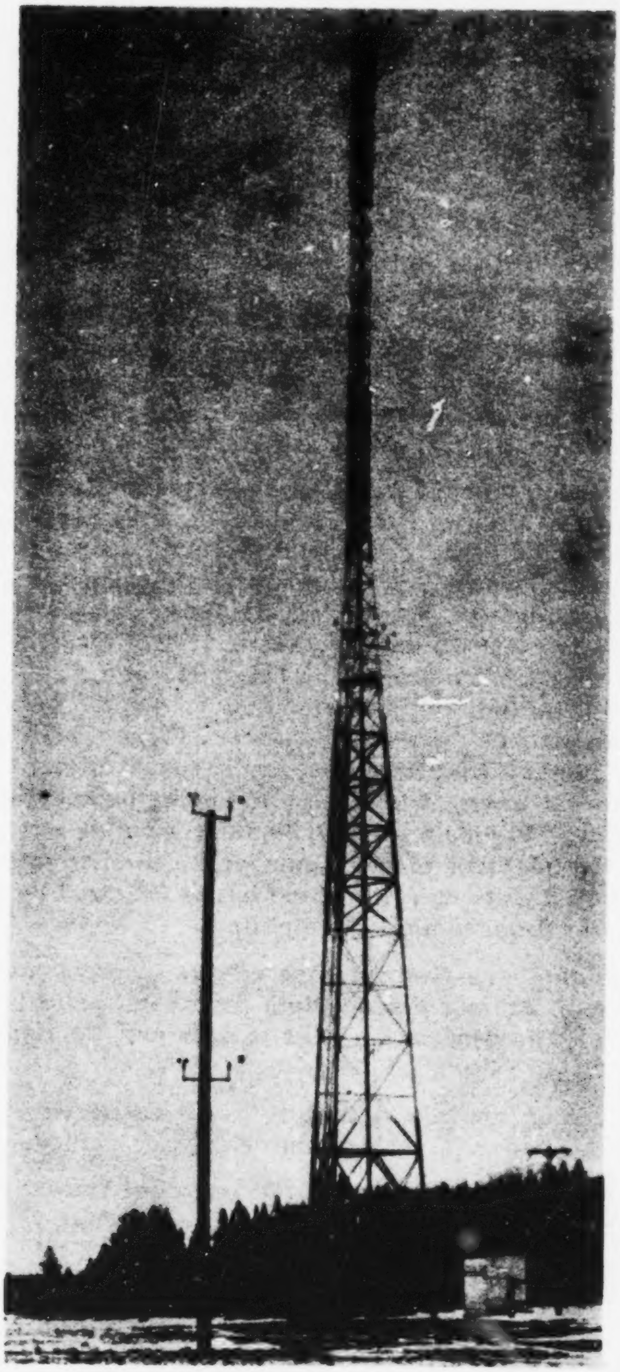

Figure 2. View of 250-foot meteorological tower and instrumented pole along the lake shore at the Big Rock Point Nuclear Power Plant.

1. Stationary Horizontal Distribution. There is a natural subdivision in this category near shore lines. The most general case is horizontal variation primarily along wind. In this case the diffusing plume is entirely over land or entirely over water. A particular but important case is horizontal variation primarily across wind. Here the wind direction is parallel to the shore line, so that one side of the plume has a land trajectory and the other side a water trajectory.

2. Horizontal Distribution Varying with Time. This type of variation may be associated with such factors as the diurnal variation of wind speed and lapse rate, a frontal passage, or a shift in wind direction resulting in a change of upwind surface roughness. The varying field of air flow associated with a regime of land and the lake breezes near a shore line is an excellent example of this type of diffusion in transitional states.

Three aerial photographs of smoke released from the meteorological tower at the Big Rock Point Nuclear Power Plant illustrate very well some of the complex diffusion patterns in transitional states with a stationary horizontal distribution as specified above. These photographs, taken in July 1961, are shown in Figures 3, 4, and 5. Figure 3 shows the behavior of the smoke plume with a northwest wind from over the lake. The initial spreading of the smoke is limited, but diffusion becomes rapid as mechanical and thermal turbulence develop over land. Figure 4 illustrates looping of the plume under unstable conditions with thermal turbulence in southwest winds, with the plume being brought down to the lake surface. Figure 5 is an especially striking photograph which shows the behavior of the plume with a west to west-southwest wind. Initial diffusion is limited but is followed by very pronounced lateral spreading of the plume.

Detailed analyses of shore-line effects found at the site of the Enrico Fermi Atomic Power Plant have been given by the authors.[17, 18] The general findings to date may be summarized as follows:

1. Values of Sutton's virtual diffusion coefficient C_z are characteristic of those for a 3-minute sampling period.

2. Values of Sutton's virtual diffusion coefficient C_y are characteristic of those for a 1-hour sampling period.

3. The wind at 96 feet is relatively strong, 12.4 mph averaged over a 3-year period, in comparison with that at the same height over a uniform land surface.

4. A lake-breeze inversion occurs frequently in late spring and early summer.

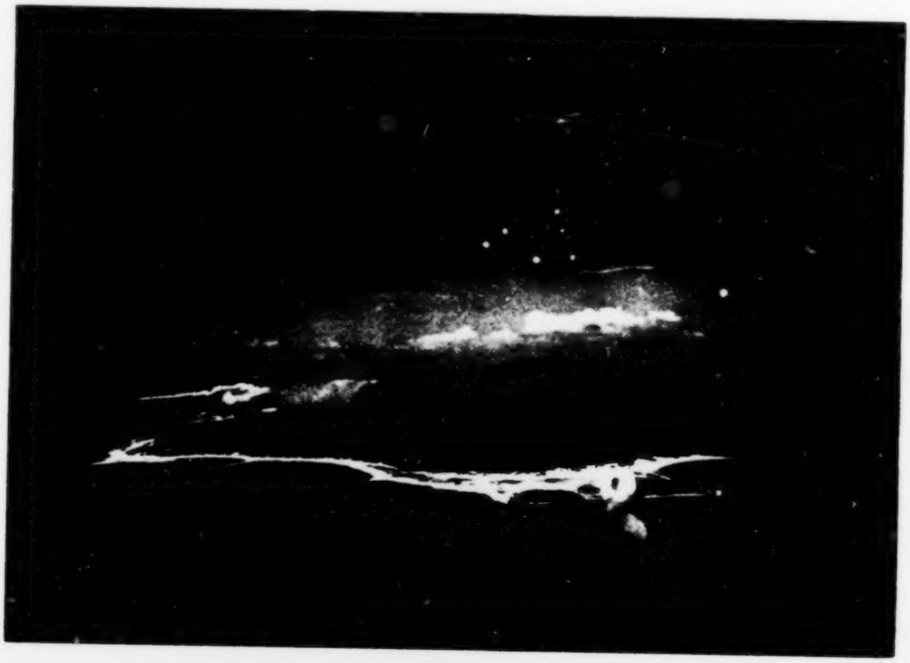

Figure 3. Smoke plume behavior with a northwest wind from over the lake at the Big Rock Point Nuclear Power Plant.

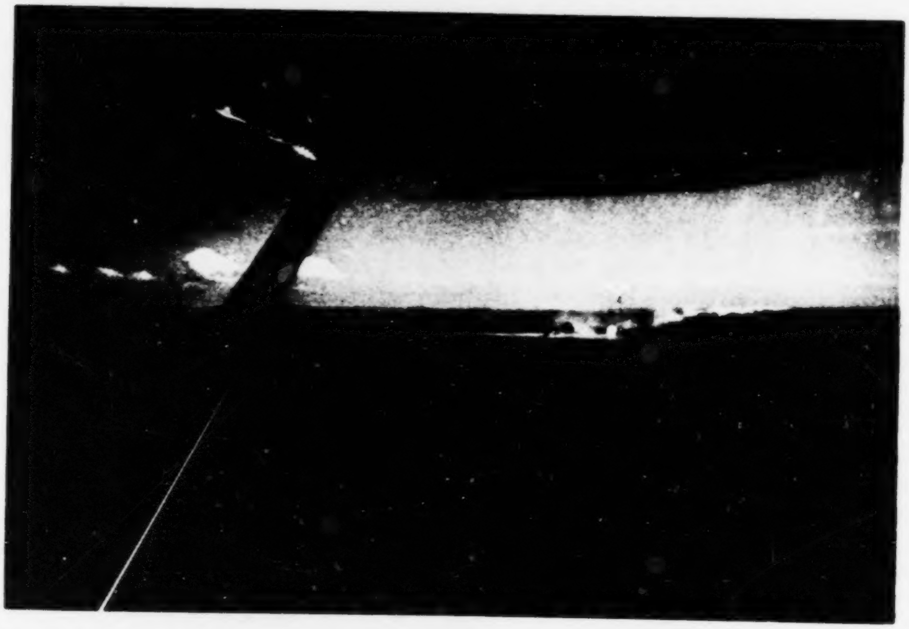

Figure 4. A looping plume caused by thermal turbulence with southwest winds at the Big Rock Point Plant.

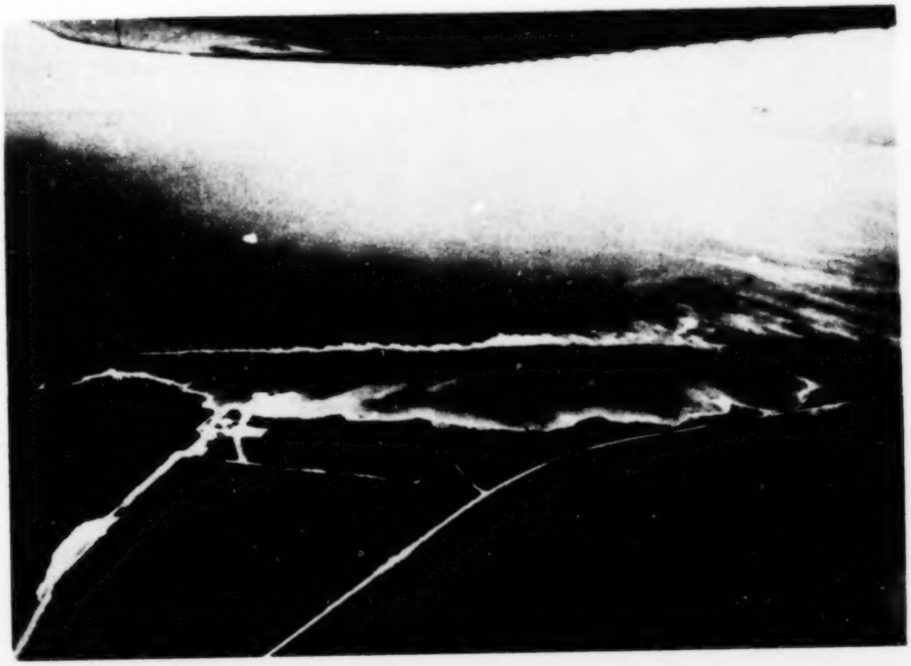

Figure 5. Lateral shear in the smoke plume at the Big Rock Point Plant with west to west southwest winds.

5. This lake-breeze inversion moves inland about 4 miles on the average, and diffusion improves with distance inland from the shore line.

6. Prolonged inversions caused by the advection of warm air over the cold lake occur, but extend no more than 8 miles inland, with improving diffusion over that distance.

7. During stagnant anticyclones the difference in horizontal air density from water to land results in local winds of sufficient strength to provide substantial natural ventilation.

8. Measurements to date indicate that there is considerable natural ventilation at the shore line of a large lake.

Although the researches mentioned above were not conducted near a city, it is clear that a city situated on a shore line will be subjected to a number of localized meteorological influences; ascertaining their exact nature will require comprehensive measurement programs.

Diffusion in Other Transitional States - Diffusion in transitional states near shore lines has been singled out for special attention because the authors are engaged in field measurement programs near shore lines. It is clear, however, that the study of diffusion in many other types of transitional states is of fundamental importance for an adequate understanding of the dispersive processes at work in the air over cities. For example, diffusion within wooded and forested areas has received relatively little attention. Trees have a pronounced effect on local stability patterns in the air below, around, and above them and in addition have a filtering action in removing particulates. Although there have been a number of studies of air flow in valleys[3, 5, 16], many more measurements of wind speed, direction, turbulence, and temperature lapse rate in and near cities situated in valleys are urgently needed. The influence of valley cities in heating the air flowing over them and the possible effects of this heating on air flow patterns during very light winds should be investigated thoroughly for such cities.

Atmospheric Pollution by Aeroallergens

It is estimated that some ten million Americans are seriously inconvenienced by aeroallergens, airborne substances which cause allergic reactions in sensitive individuals. Ragweed pollen is probably the worst offender among the aeroallergens. There is good evidence that man's land-use practices are leading to increased production and wide aerial distribution of ragweed pollen. It is surprising, therefore, that practically no attention has been paid to this important public health problem until recent years, especially since remedial measures can be taken and others uncovered if adequate research is conducted.

Meteorological aspects of the production, transport, and deposition of ragweed pollen are being investigated at two centers: the University of Michigan and Brookhaven National Laboratory. The importance of aeroallergens as a national public health problem requires the establishment of other centers for the study of the many complex problems involved.

Among the techniques developed at Michigan is that of growing preseasonal ragweed plants that pollinate in June, well before the regular pollen season, which extends from mid-August through September. Since the preseasonal plants are the only ones pollinating in the area, the source of pollen in the air is clearly established as the experimental ragweed plot. Such a plot,[6] containing over 3000 ragweed plants developed from seedlings in the greenhouse and located on the farm lands of the State Prison of Southern

Michigan at Jackson, is shown in Figure 6.

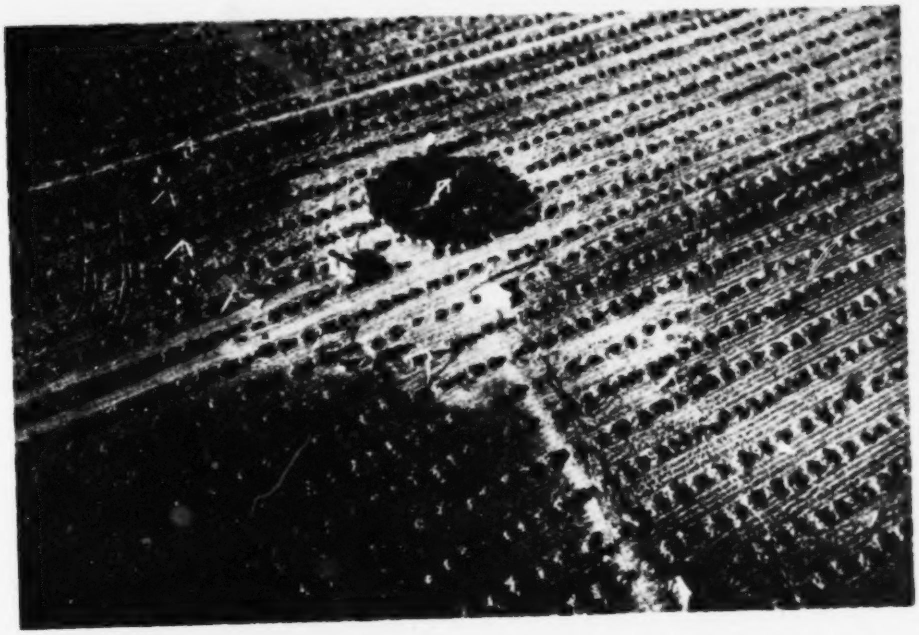

Figure 6. Ragweed pollen plot at the State Prison of Southern Michigan, Jackson, Michigan.

Determining the sources of pollen found within cities is an important problem that awaits solution. Does the pollen come from ragweed plants within the city, which might be destroyed by spraying, or from sources well outside the city, which would be less amenable to control? Some of the features of an experimental program designed to find answers to such questions are illustrated in Figure 7. The map shows the route followed by an instrumented automobile each day during the regular ragweed season as it traveled through Ann Arbor into the adjacent farm lands and back to the city.[25] The shaded areas along the route give the vegetative characteristics of the farm lands. The density of ragweed stands was estimated by the botanists associated with the project. The results of this study are being prepared for publication.

The production and release of ragweed pollen by the plants occurs mainly from 7 to 11 a. m. on clear mornings. Precipitation or prolonged fog in the morning will delay and reduce substantially the pollen emission. Our research has shown that meteorological conditions during May and June have a significant influence on the subsequent pollen crop. Objective forecasting methods,that are now being developed hold promise of yielding forecasts of pollen concentrations on both a daily and a seasonal basis.

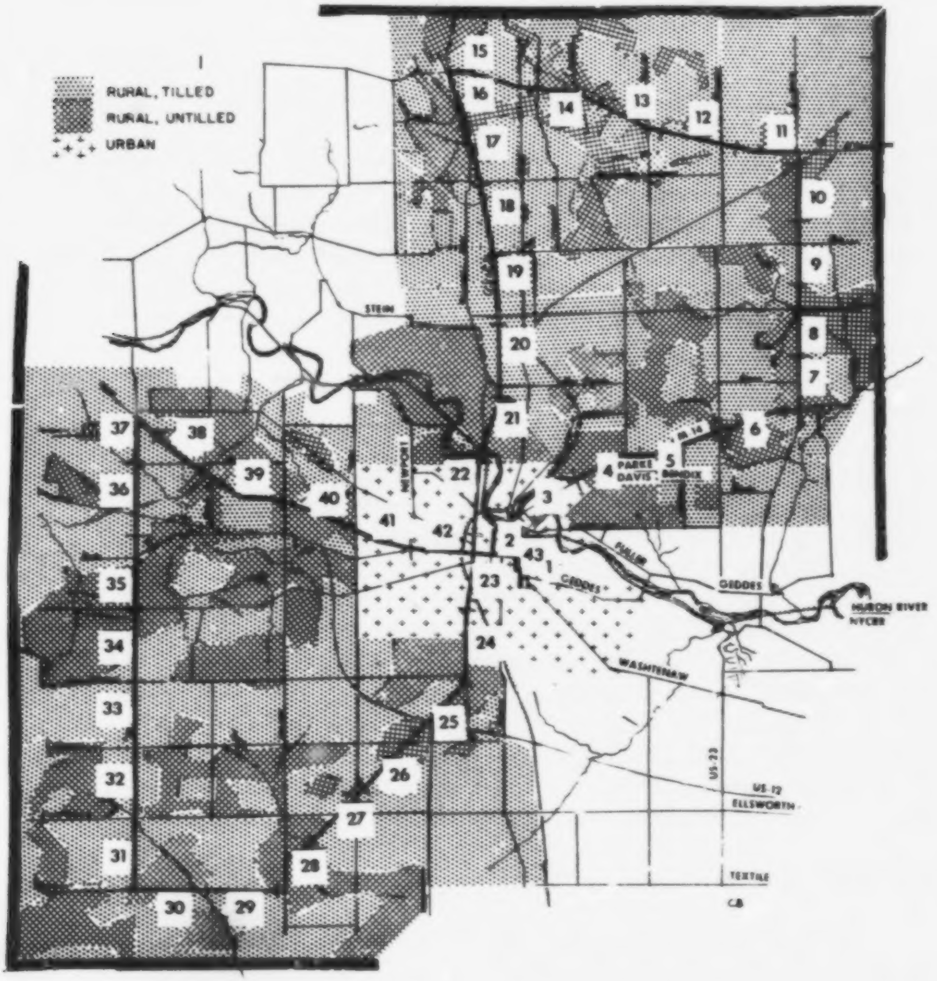
RURAL, TILLED
RURAL, UNTILLED
URBAN
STEIN
PARKE DAVIS
BENDIX
M-14
FULLER
GEDDES
GEDDES
HURON RIVER
NYCRR
WASHTENAW
US-23
US-12
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Figure 7. Route of mobile sampling program through Ann Arbor, Michigan, and surrounding areas.

There is evidence that the sensitivity of many individuals to ragweed pollen is a function of the current meteorological conditions. This phase of the problem has been barely touched, and many measurement programs will be required before significant progress is made.

Since source strength, atmospheric dispersion, and receptor reaction are all dependent on fluctuating atmospheric conditions, it may be that the pollen dispersion problem represents the transitional state problem in its ultimate meteorological complexity.

Although ragweed pollen is, medically speaking, the most important of the aeroallergens, there are many others, including spores, rusts, and smuts. Carefully devised measurement programs are needed if we are to make progress in combating this growing public health problem.

RECOMMENDED MEASUREMENT PROGRAMS

The following outline of recommendations is not meant to be inclusive. It represents only those programs that are urgently required if continued progress is to be made. Comprehensive coverage of the instrumentation currently available and in use, its advantages and disadvantages, methods of mounting, etc., is available elsewhere.[14] For this reason only general outlines of the needed programs are given here.

Standardization Studies

Such a variety of measurements have been proposed and undertaken from time to time that a serious attempt to achieve even limited standardization of requirements is an important next step. Valuable progress in that direction has recently been made,[7] but even more fully detailed specifications are now required. It may be necessary to set up a specific project for the purpose at some appropriate center, with provision for consultants to aid in the essential decision making. Examples of specifications needed are as follows: the height and exposure of wind sensors, permissible limits in the response characteristics of wind sensors used to measure atmospheric turbulence, and minimum accuracy requirements for lapse-rate temperature measurements.

Air Pollution Climatology Studies

It is essential to establish air pollution climatologies for a number of cities of various sizes subject to various climatic regimes and with a variety of terrain features. Many of the problems described in earlier sections will be solved most expeditiously by an intensive program of installing appropriate meteorological and sampling equipment on existing and future television towers.

Meteorological and sampling programs that utilize TV towers have been proposed for a number of years,[12] but little progress has been made in implementing the proposals. H. W. Baynton and associates were responsible for instrumenting the first tower, WJBK-TV, located in northwestern Detroit, as part of the Detroit-Windsor International Air Pollution Investigation.[20] This installation was later placed under the care of the Meteorological Laboratories of The University of Michigan. Temperature-measuring units are installed at heights of 20, 300, 600, and 870 feet. The top portion of the 1050-foot tower consists of the radiating antenna. Figure 8 is a photograph of the tower showing the platforms at 300, 600, and 870 feet, where the artificially ventilated temperature sensors are mounted. Figure 9 shows the lowest sensor mounted beneath the platform at 20 feet. It is proposed that all the sensors be relocated on booms extending horizontally from the tower to minimize the possibility of errors due to radiational heating or cooling of the tower during the day or at night.

A recent detailed study of air pollution in Nashville, Tennessee, led to the installation of wind speed and direction transmitters at 251-and 501-foot levels on the WSM-TV tower.[30]

Until more definitive standards for tower instrumentation can be established, it is proposed that temperatures or temperature differences be measured at 200-foot intervals if possible, with an accuracy of 0. 20°. Because of the positions of tower platforms, instruments may have to be spaced at greater intervals. Anemometers and wind vanes should be mounted at the same heights, and the response characteristics of the vanes should be sensitive enough to justify their use as accurate sensors of the horizontal component of atmospheric turbulence. A high-grade turbulence sensor, such as a rapid response bivane without excessive overshoot for all ranges of turbulent eddies, should be maintained at the station at a level of 200 or higher. All data should be recorded at the base of the tower.

Installations of this type should be established at a number of cities of various sizes and with various climatic and terrain features. With such installations in operation it will be possible to study diffusion over cities in uniform and steady states and in a wide variety of transitional states.

Supplementary wind and turbulence data would be obtained from wind sensors on 30-foot (10-meter) masts at a limited number of other stations in and near the city and in the streets on horizontal cables stretched between buildings, well above the immediate influence of street traffic. Precipitation measurements should be taken by means of one or more recording rain gages in locations with good exposures.

It must be emphasized that well-designed programs of atmospheric sampling must supplement the meteorological measurements if results are to be significant.

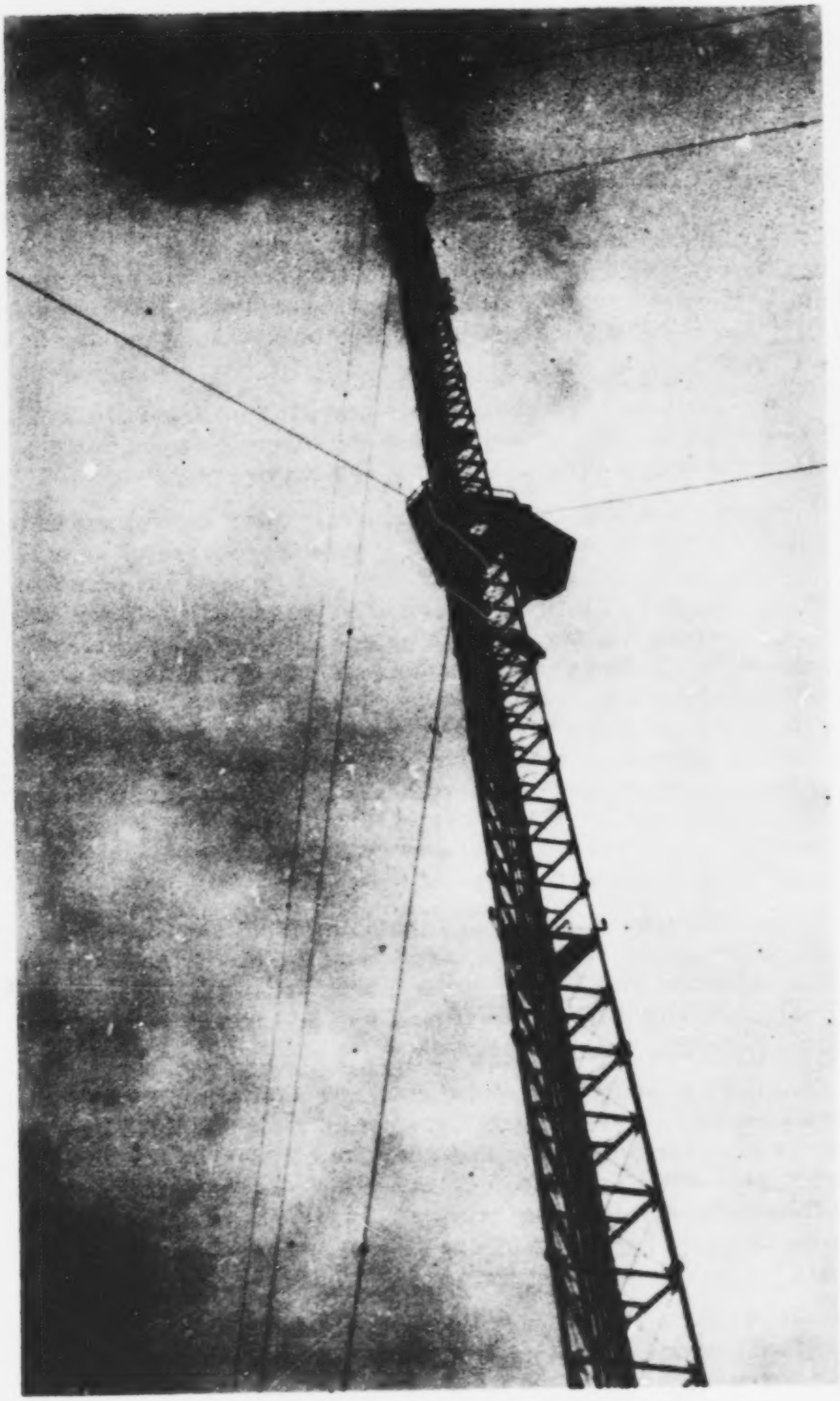

Figure 8. View of the WJBK-TV tower, Detroit, Michigan.

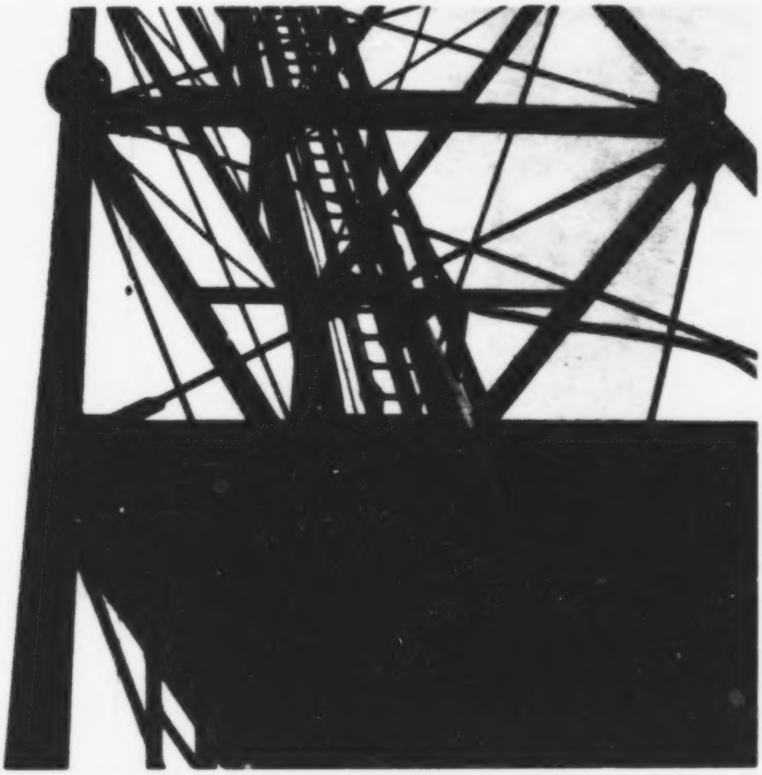

Figure 9. Detail of the WJBK-TV tower showing the lowest sensor beneath the platform at the 20-foot level.

Aeroallergen Studies

The prime requirement for advance in aeroallergen studies is the development of a simple and accurate sampler for pollens such as those of ragweed. An isokinetic sampler[9] is required for accurate sampling of ragweed pollen (18μ), but such a sampler presents severe design problems. The sampler should be able to operate reliably without attention for a minimum period of 24 hours if it is to displace the simple but highly inaccurate gravity slide sampler.

A number of other measurement programs are needed, such as those designed to determine the variation of ragweed pollen source strength as a function of meteorological conditions, the distance traveled by such pollen, the role played by precipitation in scavenging, and the filtering action of natural vegetation on pollens and other aeroallergens.

Tracer Studies

An important technique in evaluating the dispersive properties of the atmosphere is the use of tracer substances such as ZnCdS as a fine powder or liquid uranine dye. Such tracers may be used to follow air motion and turbulent diffusion over a wide range of distances from a hundred feet or so, representing the distance between a source and an air conditioning intake, to a hundred miles or so, representing diffusion over a megalopolis such as that along the east coast.

Model Studies

Model studies in wind tunnels have been most useful in the past in estimating the amount of aerodynamic downwash of plume gases occurring in the lee of buildings.[13, 26] A second important application is in delineating the details of air flow around buildings.[8] Much remains to be done in using wind tunnel model studies to predict the effect of nearby terrain features on the movement of contaminants in their vicinity. Existing programs should be extended and new programs should be established to permit wide and more effective use of this powerful tool.

Turbidity and Conductivity Studies

Certain types of studies are required to assess long-term trends in urban pollution levels. A network of turbidity stations has been established, but the areal distribution of this network should be increased.[23] It has been known for some time that the electrical conductivity of the atmosphere is related to its particulate pollution content.[29] The use of this method to assess long-term trends in pollution was strongly recommended a number of years ago,[12] but no action has resulted. Calibration methods should be developed and an active program for measurement of electrical conductivity in the atmosphere and study of its relation to particulate pollution should be established in a number of cities.

Carbon Dioxide Studies

The possible influence on our climate of increased CO_2 in the atmosphere resulting from our combustion of fossil fuels should be thoroughly studied. For an adequate program, CO_2 should be measured on a routine basis year after year at a number of points far from sources, such as large cities. Routine observations of CO_2 on a number of oceanic weather ships would be particularly helpful.

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DISCUSSION

DR. SCHMIDT: What sort of thermometers do you use in your television masts?

PROFESSOR HEWSON: I can tell you about our own installations. We have used thermocouples more widely.

Ted Munn, what was on the TV tower?

MR. MUNN: A Honeywell Resistance Thermometer.

DR. SCHMIDT: We used thermometers also on television masts, but we had difficulties as a consequence of the large electrical field. It was unmanageable.

MR. MUNN: We have had this problem with radio towers but not television towers.

PROFESSOR HEWSON: There was some difficulty with the upper levels, but I think that was the shielding that was developed at the point. This is an important aspect to keep in mind to make sure that it is covered adequately.

The Representativeness of Local Observations in Air Pollution Surveys

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Brookhaven National Laboratory,
Upton, Long Island, N.Y.

Summary

The need for appropriate meteorological data in the evaluation of air pollution problems is now generally conceded. The natural tendency is to use existing observational data whenever the material seems pertinent. In investigations by the Brookhaven Meteorology Group, data from a number of sources, including tower and surface observations, have been compared. Depending on the circumstances, both the differences and similarities are striking. Enough information is now available to indicate situations in which data may be validly transferred from one site to another and those in which transfer should not be attempted. Careful estimates of wind and stability distributions for sites with complex terrain may often be far superior to an inappropriate transfer of data.

With the constantly increasing interest in air pollution, there is an associated need for appropriate meteorological data for evaluation of the problems. Obtaining such information in its original form is time-consuming and expensive, and the question of the suitability of existing information naturally arises. In this paper, some of the problems involved in transferring data from one site to another are considered, and examples of suitable and unsuitable transfer are shown.

In the meteorological program at Brookhaven National Laboratory, the opportunity has arisen for the examination of data from various locations, and in this study two sets of records are used. The first includes wind data obtained from three elevated installations along the east coast of the United States. The maximum separation of these sites is about 150 miles, but all are in rather flat terrain and located near the coast. The locations of these three sites are shown in Figure 1, and are designated as Brookhaven, South Norwalk, and Delaware City.

The meteorological instruments from which the wind data were obtained were all mounted on structures above the ground. The instruments at Brookhaven were supported on a meteorological tower, those at South Norwalk on a tank, and those at Delaware City on a refinery structure. Heights of the instrumentation ranged from 150 to 350 feet above ground. The other group of records was obtained from three local airports in western New York State, all in rolling but not rugged terrain, and located

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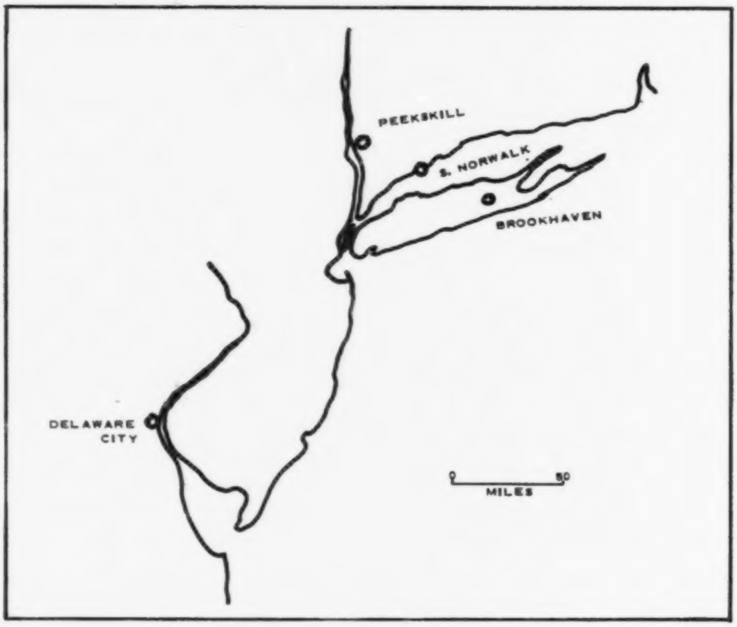
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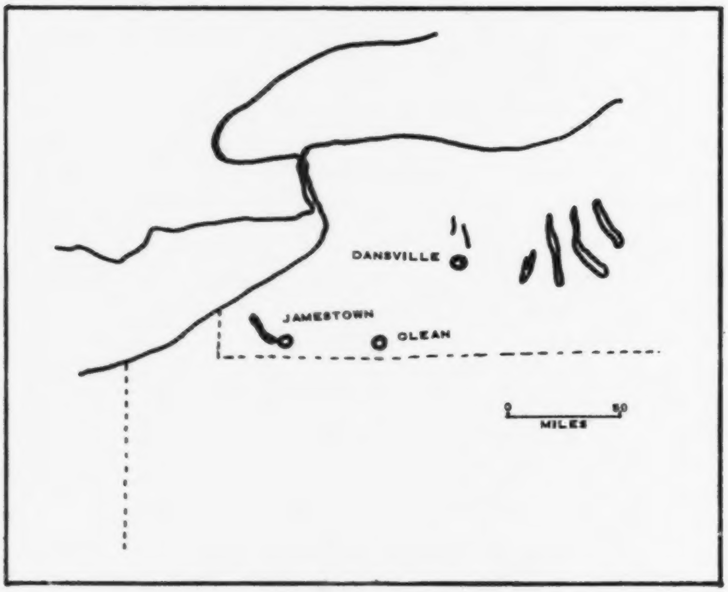
Figure 1. Coastal Sites


DANSVILLE
JAMESTOWN
OLEAN
0
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MILES

Figure 2. Inland Sites

somewhat closer to each other than the coastal stations. Figure 2 shows the relative positions of the inland stations: Dansville, Jamestown, and Olean. At these sites the meteorological equipment was mounted about 30 feet above ground, so that all of the data are low level.

In comparison of the data, only wind directions are used, both because the height differences of the coastal stations are considerable, and because at least one of the anemometers in the inland group probably was defective.

COASTAL STATIONS

Figures 3 and 4 represent wind roses at the three coastal stations during winter and summer, respectively. Although the figures show a distinct seasonal change, the wind roses of the

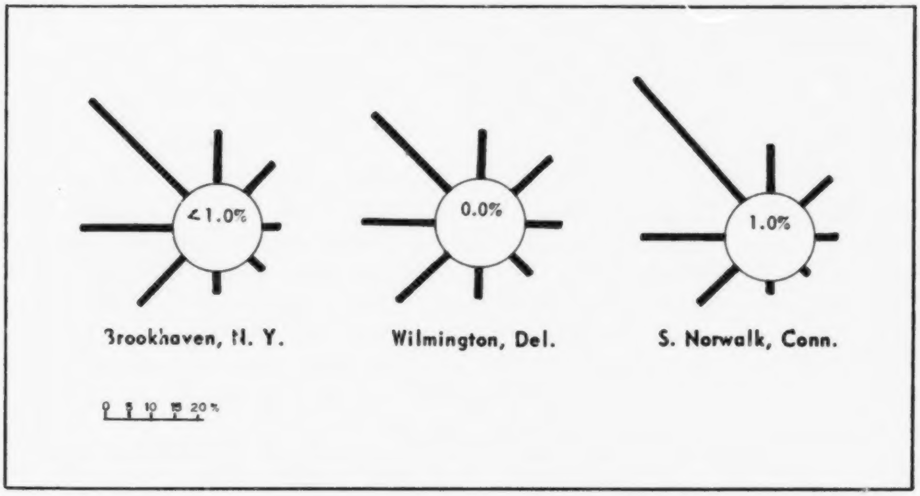

Figure 3. Coastal Sites, December, January and February

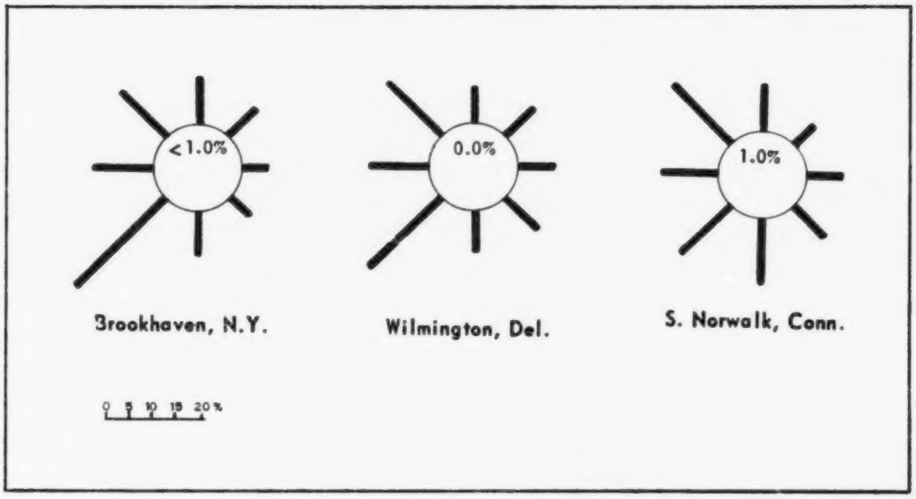

Figure 4. Coastal Sites, June, July and August

three stations are quite similar. In the winter, each of them shows a definite NW maximum with important contributions from SW, W, N, and NE as well, but none of the stations is particularly affected by winds ranging from E through S. In the summer wind roses, Figure 4, similarities are also apparent, although the South Norwalk record shows a little more frequency of S and NW winds as opposed to a south-westerly flow, which is predominant at Brookhaven and Delaware City. The harbor orientation favors a more southerly sea breeze at South Norwalk, and a drainage wind down a shallow valley at night contributes to the northwesterly maximum.

Figures 3 and 4 show that calm winds (entered as percent in the center of the circle) are exceedingly rare at all stations.

INLAND HILLY STATIONS

Similar wind roses for winter and summer are presented in Figures 5 and 6 for the hilly inland stations: the direction distribution for these stations is shown to 16 rather than 8 points. One would be hard pressed to identify these wind roses as coming from the same general area of the country. The differences are marked, with Dansville showing a strong tendency for NW-SE flow, Jamestown generally recording winds from S through NW, and Olean reflecting sharp peaks from the SW and E, especially in the summer.

The Jamestown station shows a very high percentage of calms, which may reflect a defective instrument, since no other reason is apparent.

These marked differences cannot be explained on any general meteorological grounds, but the reasons for them become clear on inspection of terrain maps of the local areas, Figures 7, 8 and 9. Dansville, shown in Figure 7, lies in a pronounced NNW-SSE valley, which channels the flow very sharply. Presumably there would be a strong diurnal variation in this valley with drainage winds from the SSE at night and up-valley winds from the NNW in the daytime. The map of Olean, Figure 8 shows quite clearly the reason for the predominance of east and west winds at the site, since the main configuration of the valley favors such flow. It is not obvious on a map of this scale, but closer inspection of detail would show a sharp cut directly south of the station; presumably the strong tendency toward S winds represents a drainage wind down the slope. The map of Jamestown, Figure 9, is not quite so easy to interpret, since the terrain features are not as sharply marked as those of the other two sites. Particularly, the very high percentage of calms is difficult to explain, and for this reason it is thought that the anemometer may have been defective.

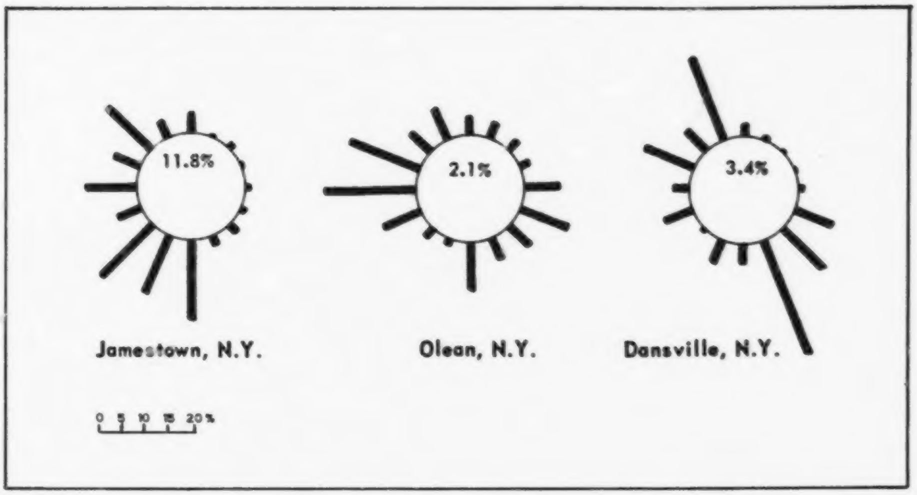

Figure 5. Hilly Sites, December, January and February

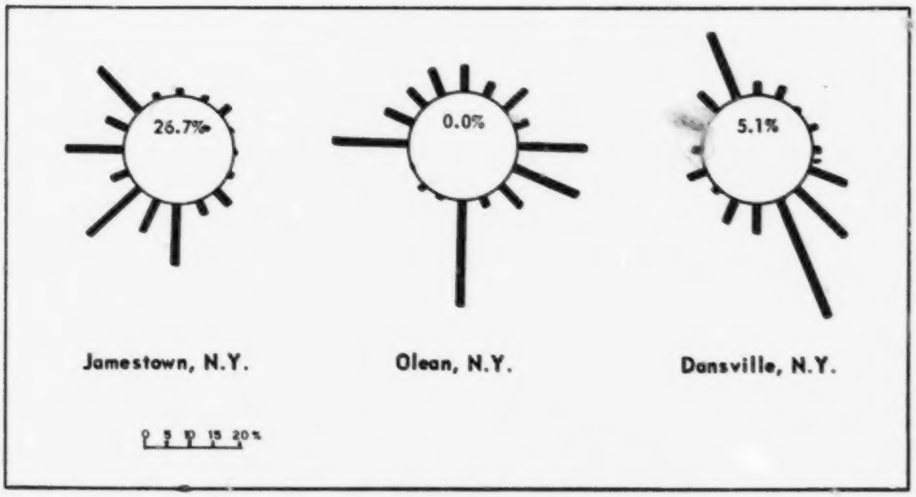

Figure 6. Hilly Sites, June, July and August

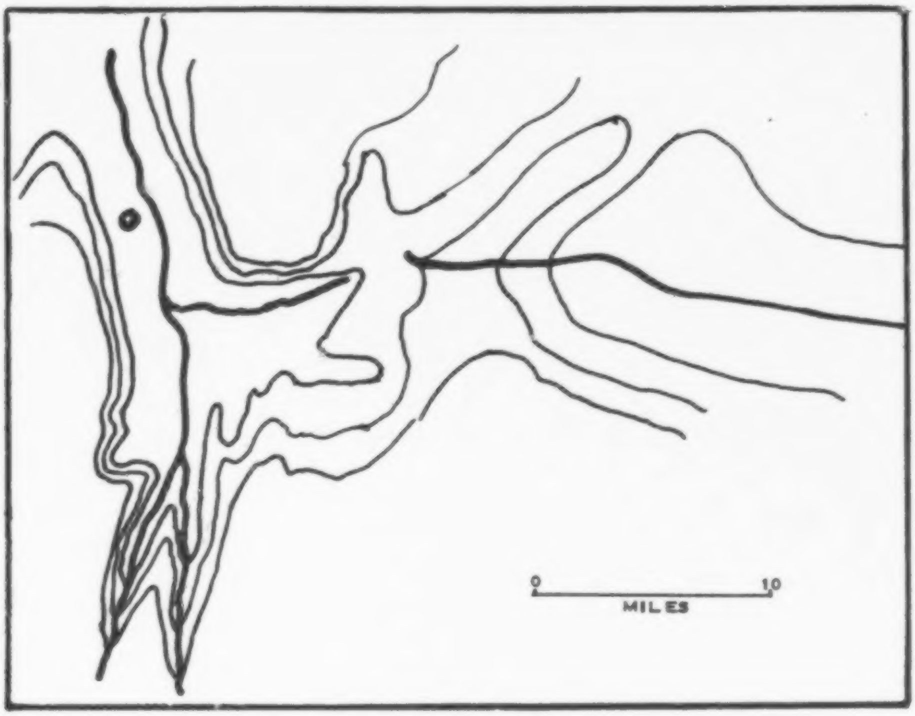

Figure 7. Terrain map – Dansville, N.Y.

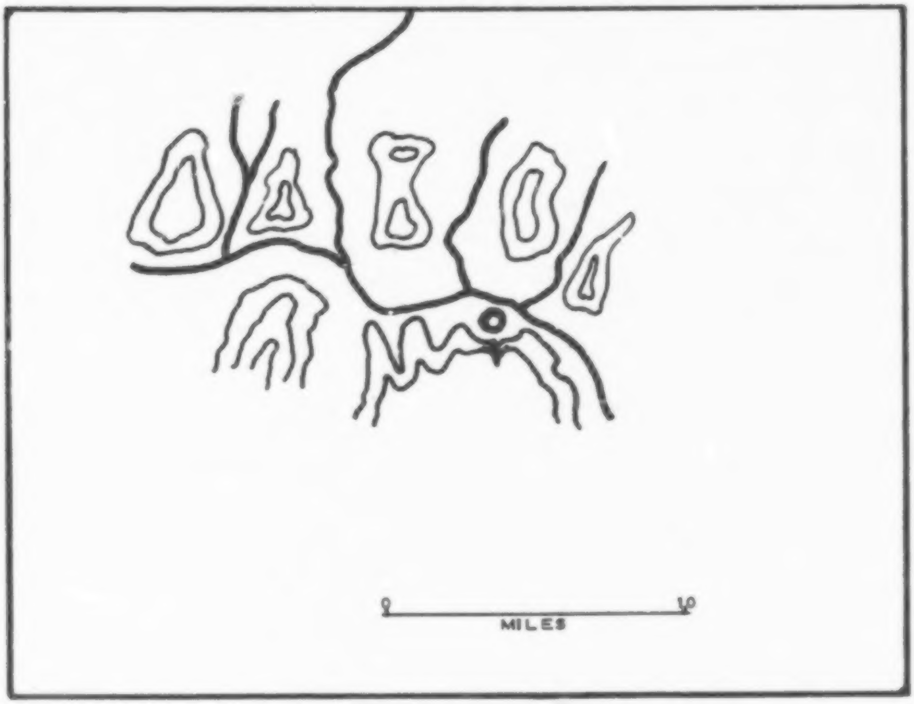

Figure 8. Terrain map – Olean, N.Y.

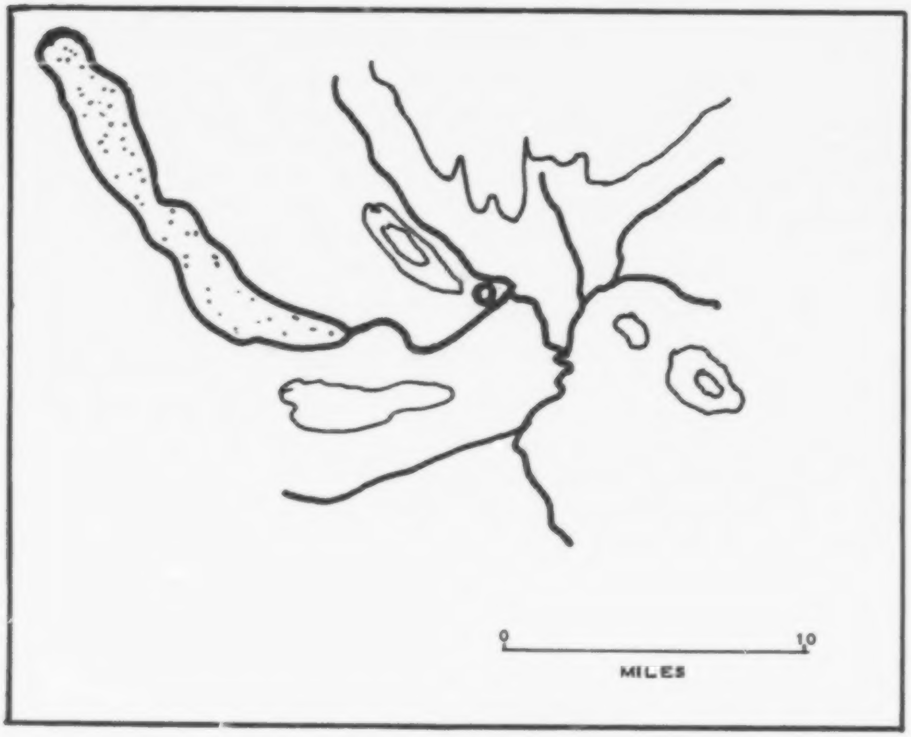

Figure 9. Terrain map – Jamestown, N.Y.

CONCLUSIONS

This brief review indicates that prospects for the use of existing meteorological data for air pollution studies are both encouraging and discouraging. Essentially the main conclusion of the study is that in each case that requires data, the decision as to the means of acquiring it should be made by a person familiar with micrometeorology. If the terrain and altitude considerations warrant it, transfer of data among similar sites, even over a fairly wide area, is a perfectly reasonable procedure. Certainly from a site-survey point of view, the wind roses of Brookhaven, South Norwalk, and Delaware City are substantially identical.

On the other hand, it seems equally clear that there is little point in devoting any study to data transfer in rough terrain. A careful inspection and evaluation of the site may produce an estimate of the wind distribution which would be superior to that obtained from a misguided attempt to transfer data.

DISCUSSION

PROFESSOR HEWSON: There is one type of variable that shows up in that Jamestown wind rose that I don't think you mentioned. Is there not a possibility that since the peaks in the wind rose are from west, southwest, south, and so on, and you had minima in between these points -- may this not indicate a bias on the part of the person who was reading the observations? I noticed this, and my interpretation was that it was perhaps easier to write southwest or west rather than south southwest.

MR. SMITH: I think that anyone who has ever done any reading of such data would have to agree with you. This is one of the points that I wanted to make really, that when you select information of this kind you accept the problems as well as the data. I think any one of us will show a bias, particularly someone who isn't scientifically curious about it. That certainly could be what happened in that case.

We performed a study on the problem some time ago; we had two girls read two full years of wind-speed data, and they were to read this information to a tenth of a meter per second. The records were perfectly satisfactory for this. If you look through the data and make a frequency distribution, of course, 0.5 and 0.0 show up far more frequently than anything else. There is no question about it.

MR. KALPERN: What type of stations were these actually? Were they 24-hour observations?

MR. SMITH: Yes, they were.

MR. KALPERN: Were they Weather Bureau stations?

MR. SMITH: They were Weather Bureau stations or Airways stations.

MR. KALPERN: What period of time?

MR. SMITH: The records I showed you covered a period of two or three years.

MR. KALPERN: How long ago?

MR. SMITH: I think the earliest date was about 1956 and the latest date was very recent.

Present and Future Needs for Meteorological and Air Quality Observations in Canada*

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Summary

Air pollution meteorological data cannot be assessed without knowledge of the objectives of urban air pollution studies. A set of objectives and requirements for meteorological support is outlined. Some typical Canadian air pollution surveys now in progress are discussed. Field data are assessed and recommendations made. The advantages of national or international uniformity in methods of measuring, reporting, and storing air pollution meteorological observations are presented.

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Problems Associated with Forecasting Air Pollution Over an Urban Area

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Summary

The need for a more specialized observational program scaled for air pollution studies is discussed in terms of the operational air pollution forecasting service in the Los Angeles Basin area of Southern California.

Any air pollution study requires an accompanying body of meteorological data. This holds true both for the simple survey that determines whether there is air pollution, and for the all-out effort of continuous measurement designed to detect pollutant levels and alert a community to the approach of pre-determined danger levels.

In none of these situations is one likely to find the meteorological data in the form and at the location desired. This is a characteristic of such data as presently gathered. The location of weather stations and the type of observations reflect a preoccupation with aviation problems. In former days, agricultural interests received all the attention. That was the period of emphasis on temperature and precipitation reports gathered by a multitude of cooperative stations. The city office was in its ascendency, although it served more as a climatological clearing house than a source of detailed weather information about the city itself.

The airport weather station has now replaced the city office at most urban centers. What the study of air pollution needs, though, is a return to the city office, a city office that conducts an observational program geared to urban problems.

In this paper, we will discuss these problems in the light of the forecasting program conducted by the Los Angeles County Air Pollution Control District.

GENERAL DISCUSSION

Instead of forecasting the general weather of whole states or sections of the country, the Air Pollution Control District concentrates on predicting the air pollution conditions over one coastal basin. Through inter-agency agreements, Los Angeles County provides meteorological forecast service to two of the three other counties that share the region included in the term, Los Angeles

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Basin. Altogether, then, the forecast area encompasses about 2400 square miles, running from the Pacific Ocean on the west and south, inland 77 miles to the fringing mountains to the east, and 31 miles to the mountain boundary on the north.

Beyond these mountains lie the California deserts that together with the Pacific Ocean control the ebb and flow of the air over the Basin, a transport mechanism that directs the movement of the Los Angeles smog cloud from its first formation to its final removal.

The forecast problem in this rather limited area basically is the prediction of two meteorological conditions – the horizontal wind flow and the stability of the air mass. Knowledge of these conditions and of the amount of solar radiation that will be available at the surface should theoretically produce a good forecast of the resulting air pollution situation.

Some rather formidable obstacles stand in the way of the achievement of such a perfect forecast. These are, as would be expected, forms of ignorance: ignorance regarding the future meteorological doings of nature, and further, ignorance of the actual conditions that have led to smog attacks in the past.

In the latter situation, the air pollution forecaster finds himself in a position similar to that of the early Weather Bureau men who had to make predictions without the benefit of an understanding afforded by the frontal theory of storm formation and growth. This analogy applies specifically to the photochemical type of smog. To the extent that low-level, mesoscale, meteorological measurements are not made synoptically with air quality measurements, it applies also to the air pollution problem in general.

PROBLEMS INVOLVING THE ATMOSPHERIC-CHEMICAL REACTIONS

The cause-effect relationship between hydrocarbon-producing sources and photochemical reactant products forming smog has been firmly established since 1952 by Haagen-Smit. The intermediate steps in this reaction, the way variations in initial pollution conditions may alter the course of the reaction, have remained unknown, however. Within the past year, experiments with large controlled-environment chambers have begun to produce results that should increase our knowledge in this regard. In the meantime back at the forecast office, the forecaster is endeavoring to apply his knowledge of the reactions. This is most difficult, to use as colorless an understatement as possible, in our uncontrolled natural atmospheric environment.

Experience has taught the Los Angeles smog forecasters that some of the most apparent smog attacks (apparent to the taxpaying citizens' sense of smell and sight) are not accompanied by correspondingly high concentrations of oxidants or ozone. Other situations reveal the reverse – high concentrations of pollutants, but no noticeable smog.

Then, too, there are differences in smog effects that depend on the particular section of the Basin that is involved. For example, in downtown Los Angeles the eye-irritating properties of smog are most pronounced, but ozone values are relatively low. It is at outlying stations to the north and east that alert-level ozone values are usually measured. In these suburbs eye irritation may or may not accompany the ozone. Further east, in San Bernardino and Riverside Counties, elevated ozone or oxidant values may be recorded, but little or no eye irritation is noted. These high values have been accompanied by visibility observations ranging from 30 miles to 1/2 mile.

Plant damage is another manifestation of air pollution on which the forecaster must give advice. Here more unknowns obscure the forecaster's crystal ball. Plant-damaging attacks of smog have been noted everywhere in the Basin and even across the fringing mountains in the Mojave Desert. Apparently the concentration of smog need not be very high to produce plant damage, since such effects are noted in areas that so far have not reported eye irritation.

THE OPERATIONAL FORECAST

Operational forecasts by the Air Pollution Control District are designed for two general uses: public and internal. The latter is the information on which the air sampling operation is conducted, and probably closely resembles the type of service given any organization by its meteorological supporting unit. The public dissemination of smog forecasts is somewhat unusual and for that reason is more fully discussed.

The issuance of smog forecasts to the Los Angeles public began in 1952. Originally the public release of these forecasts was made in order to educate. Smog in its varying degrees of severity was not recognized by the general public as being meteorologically controlled. Rather it was thought that the source of pollution varied in strength. It was to combat this idea that the forecasts were issued, always relating the expected pollution in terms of pertinent weather conditions. A secondary consideration involved in the issuance of a public forecast was the District's overloaded switchboard on bad days. Complaints came thick and fast whenever the weeping-eyed populace could grope its way, via telephone dial, to the District's complaint desk. The forecast, it was hoped, would cut out that portion of the public that called just to tell the District that it was smoggy. If it was already in the forecast, the reasoning went, they all could save their telephone message units.

The air pollution forecast has been the basis for various systems of limiting emissions when poor dispersion conditions were expected. For example, open fires are not allowed in the Los Angeles Basin, with but few exceptions. These exceptions, however, are also forbidden whenever stagnant air flow is forecast.

At one time, a voluntary system of restricted driving was put into effect whenever bad smog was anticipated. This took the form of a request that no unnecessary driving be done on smoggy days. Since no one, it turned out, did any unnecessary driving, this use of the forecast could not be considered a huge success. However, there is evidence that on days forecast to be smoggy, fewer than the usual number of shoppers came into town. At least, that is the complaint from the downtown merchants' association.

During the cool portion of the year, when the electricity-generating steam plants are normally burning fuel oil rather than natural gas, the forecast is used to cause these plants to switch to gas when an air pollution attack is expected. This takes the combined efforts of the power-generating systems and the gas companies. Gas, being in great demand for domestic use in winter, is provided to industry on an as-available basis. When the fuel-switch forecast is made, the gas companies have to depend on their storage facilities to provide service to all. Fortunately heavy smog attacks, while they occur in winter, do not last very long – usually only a day or two.

A major segment of the air sampling activity of the District is that done in response to the legally required monitoring service. Various pollutants, known to have toxic effects, are constantly watched through use of automatic recording instruments. A system of warning levels has been established. The first alert level is in the nature of a preliminary warning. Industries are notified to prepare for possible shutdown, if the pollution level goes higher. A second-stage alert triggers the shutdown procedure. If third-stage conditions are encountered, then concentrations are such that a danger to the public health exists and the emergency powers of the State Governor come into play.

The meteorologist is involved in this alert procedure because pollution levels exceeding the alert criteria may occur at any station in the Basin. He is then asked to predict how long the values will remain high, to what maximum they will go, and finally, what other stations may be expected to measure high concentrations of this pollutant.

If the meteorologist knew for the entire area the wind flow pattern and the depth of the polluted layer, then he would be able to answer these questions successfully. Since he doesn't know these things precisely, he does the best guessing he can. Certainly some type of telemetering system, both for meteorological and air monitoring data, would be very useful here.

Obtaining the depth of the polluted air – a sounding – presents one of the more important difficulties. At the present stage of technology the best that can be done is to obtain more frequent temperature soundings by balloons or other airborne equipment. What is really needed is an instrumented tower about a mile high, but that does seem a bit impractical even for California. Three-hundred-foot towers, as used elsewhere, would not meet the need in Los Angeles because the restraining inversion base is as much as 1000 feet or more even on the worst smog days.

FORECASTING WEATHER PATTERNS CONDUCIVE TO SMOG

Turning to the strictly meteorological portion of the forecast problem, one discovers the same lack of basic knowledge of the existing large-scale weather conditions that exists regarding the very local conditions associated with pollution concentrations. For a forecast of the Los Angeles smog conditions 24 to 36 hours in the future, it is necessary to consider past and current weather patterns and how they are changing. The basic charts used to obtain this picture are those for 500 and 850 millibars and the corresponding surface chart.

Since upper-air charts are made only every 12 hours, with considerable space between network stations, the forecaster is severely limited in his efforts to extrapolate. This would not be such a problem if we were dealing with dominant features of a weather map – the deep lows and the prominant highs – but air pollution is a child of weak weather systems. These are often barely detectable, even after the fact. Any changes at all in conditions either at the surface or aloft, may be important to the forecast. With present weather observing schedules, these subtle changes are almost bound to be noted too late to do any good.

In an effort to detect small changes in weather conditions the Los Angeles forecaster resorts to a close watch of surface pressure gradients between coastal and inland stations. Generally, an increasing onshore gradient results in a rising inversion and a lessening of the smog. An increasing offshore gradient usually indicates the reverse, until the change is too boisterous. In this latter situation, the air mass lying on the desert side of the mountains bursts its bounds and sweeps down over the coast. This is the "Santa Ana", a wind that carries the smog far out to sea and in certain sections is strong enough to carry off part of the real estate as well.

The forecaster feels most confident about his forecast for the occurrence of smog when the pressure gradients are near zero and show no great change during the preceding hours. Theoretically, the low-level wind flow that is responsible for the accumulation and subsequent movement of smog is caused by these pressure gradients. When strong gradients exist, this relationship of pressure and wind flow is evident. But with weak gradients the winds appear to be uninhibited by such theoretical considerations. It must be assumed that even in this situation the wind does indeed flow from high- to low-pressure areas. The apparent contradictions encountered must be the result of inaccurate or imprecise pressure measurement.

Even in the low-lying coastal area of the Los Angeles Basin, the first-order weather stations (military and Weather Bureau) sometimes report as much as one, and often as much as one-half, millibar difference in pressure between stations only 6 miles apart. This, it would seem, represents a basic inaccuracy in pressure readings at one or the other station. A thorough check on pressure-observing practices seems indicated so that this uncertainty can be minimized.

Even with these more obvious errors in pressure readings corrected, there still remains the problem of preciseness. In a situation of weak gradients, it is not at all unlikely that definite wind flows will develop, indicating a response to some gradient, weak as it seems to be. Possibly, a more refined pressure observation network, refined both from the standpoint of instrumentation and geographical spacing, would reveal the cause of the observed wind flows.

UNTAPPED SOURCES OF WEATHER DATA

One possibility of getting an enlarged picture of the basic pressure patterns is to utilize temperature. Temperature is related to pressure and there are many more temperature than pressure observations available for study.

In the Los Angeles Basin, in addition to the regular network of meteorological stations, there are a great number of locations at which temperature is measured. Within the past several years it has become fashionable for commercial concerns to display temperature readings on lighted signs. Preliminary reconnaissance indicates that as a whole these thermometers have a rather uniform exposure. They are usually mounted on the roof of a one-story building in a louvered "birdhouse". The indicators are visible both from the street and inside. Telephoned in to a forecast office, these temperature reports would provide a basis for analyzing the existing temperature field. A series of hourly observations would show the change of temperature with time. Hopefully, these data could be correlated with the various types of morning air flows found in the Los Angeles Basin.

This is one method of trying to achieve full utilization of existing meteorological data. Any study in depth of a geographical area such as the Los Angeles Basin will uncover an unsuspected number of meteorological data gathering organizations. Much information could be made available to interested parties provided some means could be found for communication. No one organization appears able to afford the monetary and labor costs of setting up and running such a local meteorological network. A proposal for such a system, in which mesoscale analyses would be performed at a local analysis center, has been recently made by Todd.

SUMMARY

Problems facing the air pollution forecaster, as seen from the midst of the Los Angeles smog cloud, fall into two categories. These involve the lack of knowledge of, (1) the pollution reaction itself, and (2) the meteorological variations.

The first is being worked on by air pollution chemists and thus is outside the province of meteorologists. The second, though, must be faced by the meteorological profession. An increased emphasis must be placed on measuring the atmosphere on a scale suitable to the air pollution problem. This includes not only a relocation of observational sites back into the cities but also an increase in the density of the weather-reporting network surrounding a city. It further includes making the proper kinds of meteorological measurements.

Once this basic meteorological data is available the forecasters of air pollution may have some hope of success in predicting precisely the extent and duration of a smog episode. It is conceivable that, if necessary, the future air pollution forecast may be used to save lives even as flood and severe weather forecasts do presently.

DISCUSSION

MR. WILLIAMS: What has the batting average been on predicting smog?

MR. KAUPER: You can always get an 80 percent accuracy if you manipulate right. But we do a monthly verification on various parts of our forecast, and our verification ranges between 60 and 70 percent most of the time.

MR. LICHTBLAU: I feel that I have to say a few words in defense of the Weather Bureau. Thirty years ago we were under somewhat different circumstances, and practically all of our stations were at urban locations. I think that we have as many urban stations at the present time as we had 30 years ago, but we also have many, many airport stations that did not exist 30 years ago. So that is the way the picture has changed. And probably we will get more urban stations as time progresses.

You mentioned about the pressure observations. It is unfortunate that these inaccuracies do exist and we will try to correct this situation. But there are many agencies involved, such as the military, the CAA, and the FAA, and sometimes it is rather difficult to get uniform measurements.

There are a couple of other remarks I would like to make. I just wanted to state for the record that meteorologists are certainly interested in morbidity and health. Otherwise there would be no reason for our existence.

Yesterday the question was asked about how long it would take for Weather Bureau people to make air pollution forecasts. I think the figure was given as 45 minutes or an hour. At a Weather Bureau Forecast Center the forecaster on duty often does make informed air pollution forecasts. At certain times of the year the city piles up the collected trash instead of burning it every day as they usually do. Then the fire department will call us and ask, "Can we burn our trash today, or shall we burn it tomorrow?" And usually we can tell them within a minute or two whether they should burn it today or tomorrow.

DR. HEWSON: In 1949 a paper was published by Dr. Jones in which certain rules and definitions of chemistry were set forth. It was indicated that these should be used in air pollution forecasts. Have these rules been proved to be of value when used over a long period of time?

MR. KAUPER: The answer is that we don't use those rules.

The Need for More Meaningful Meteorological and Air Quality Observations for Mortality and Morbidity Studies

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Summary

The relationships between air pollution, meteorology, morbidity, and mortality are being studied in many countries, especially Great Britain and the United States. These studies show that more meaningful meteorological and air pollution data must be developed. Relating air pollution to health effects is difficult because the network of recording stations is sparse and because not enough is known about the diffusion, dispersion, and concentration of pollutants in the atmosphere of urban areas. Difficulties encountered in health studies of this type are discussed, and the need for descriptive meteorological and air pollution data is indicated.

The existing information concerning the effects of toxic substances upon animals and man is considerable and is derived mainly from laboratory investigations and industrial exposure studies. These data generally are concerned with above-normal concentrations and as a rule, though not always, with acute effects. It is from these data that the industrial hygienists derive the terms "maximum allowable concentration" and "lethal dose."

In considering the problem of air pollution, however, we are interested not only in the effects on man of the above-normal concentrations that may occur at times, but also in the effects of the levels of air pollution to which he is subject during the course of his daily life.

The chief characteristics of air pollution are that it is generally low in concentration and long in duration of exposure. Air pollution varies temporally and spatially in a given geographical area and also differs from area to area. These characteristics make it exceedingly difficult to arrive at meaningful average values of air pollution over a long period of time.

Moreover, the residents of urban areas, who are exposed to the effects of air pollution during their lifetimes, have great mobility. A person employed in a section of the city where he is exposed during an 8-hour day to high levels of air pollution may reside in a relatively non-polluted suburban atmosphere. Another person in the course of changes of employment may be subject to various levels of air pollution. This mobility in a population adds to the difficulty of evaluating the effects of air pollution.

Three approaches may be used to relate air pollution to health. The first is to study man in the laboratory in experimental fashion. Despite moral and legal implications, volunteer work with human subjects has produced some basic information. But this type of experimentation has of necessity been limited. We do not reject this direct approach -- it is the soundest physical attack on the problem -- but by its very nature this work must advance slowly and cautiously.

The second source of information is the controlled exposure of animals in laboratories to various concentrations and combinations of air pollution and meteorological factors. Much knowledge concerning physiological changes has been gained this way, but carrying over the results of these experiments to human beings is difficult.

The third method of evaluating the influence of air pollution and meteorology upon morbidity and mortality is to study man in his normal environment. This is the epidemiologic approach in which we are working, under the direction of Dr. Leonard Greenburg, at the Albert Einstein College of Medicine with support by the U.S. Public Health Service. We are grateful indeed for being permitted to attend this meeting and express our thoughts on the matter.

The epidemiologic method consists of a study of the conditions in a population, the distribution of these conditions, and the factors that lead to such a distribution. The condition to which we refer is the health status of the individual, which includes susceptibility to disease, illness, or death. The factors that influence these conditions and with which we are concerned are the contaminants in the atmosphere and the meteorological variations.

Among the questions which we may ask are: Does exposure to normally low concentrations in the air cause direct impairment of health? Does such low level exposure make the individual prone to infection? How important are the predisposing conditions or susceptibility of the individual when he is exposed to low levels or acute periods of air pollution? What is the combined effect of weather and air pollution on the health of New York City residents?

The several sources from which morbidity data may be obtained include the records of emergency clinics, hospital admissions and discharges, union and group medical plans, civil service groups, private physicians, and clinics. The problems of differential diagnosis enter into the collection of such information, and we would not like to mislead you into thinking that morbidity statistics are clear cut.

Absenteeism and illnesses records are available from large business firms, but in our experience they have been found to be influenced by too many external factors to be of value.

Mortality information, on the other hand, provides more definitive numbers, which include precise times of occurrence and cause. We are fortunate in New York City that the Department of Health's Bureau of Statistics, under the direction of Dr. Carl Erhardt, has for the past 15 years compiled mortality data by date of death and has recorded these on punch cards. These are two invaluable assets in our study. Only New York City, Chicago, and Los Angeles, we are reliably informed, report mortality by date of death.[1] Everywhere else the data are by date of report of death or grouped by week or month. Date of the report of death may be any time up to several days afterwards. This uncertain time element seriously weakens any attempted correlation with air pollution and weather.

Turning now to air pollution and weather, the epidemiologist asks: What indices may we use to represent the air pollution and weather to which an individual is exposed? What liberties may we take with the data collected by monitoring, sampling, and meteorological measurements in order to make such data usable in our intended statistical analyses? For through these statistical associations we will be able to develop hypotheses concerning the etiological factors and test the hypotheses developed in clinic or laboratory.

Air pollution may be considered as an independent variable, subject only to the magnitude of its sources. On the other hand, air pollution is conveyed by the atmosphere, so that it is a dependent variable with respect to meteorological conditions. The body of knowledge that has accumulated in recent years on the subject of air pollution has already given satisfactory evidence of the qualitative relationships between weather parameters and air pollution levels in the atmosphere.

But from this point on our information is weak. The more detailed knowledge of the atmospheric structure over given cities, parts of cities, given urban or rural localities -- this knowledge plus knowledge of the effects of such small-scale atmospheric conditions in varying the dispersion and diffusion of pollutants is still to be acquired.

We have become very much aware in our epidemiological studies in New York City of the lack of information regarding the variability of both air pollution and meteorology, not only spatially in the horizontal and vertical, but also chronologically. This variability points up one of our problems: how to obtain valid indices for the contaminants that may be present in the atmosphere.

We would like to offer an example of a valid index. In a survey designed to investigate the relationship between the prevalence of pneumoconiosis and dust exposure in coal mines, we might define the exposure to the air pollutant as the concentration of dust times the length of exposure. If the concentration were measured at one end of the coal shaft, our dust exposure would be invalid. First, the concentrations which were measured could not be assumed to be the same as those that had existed in the past and that may have produced the disease. Second, in the course of employment in the mines, the men would probably have worked in other parts of the mine where the measurements taken would not be applicable. Lastly, the dust measurements may prove to be irrelevant in such a study because such dust measurements in terms of weight are unduly influenced by the larger particles, which do not enter the lung at all.

A valid index is therefore one that measures what it is intended to measure, and it can be judged only in the light of previous knowledge and investigations.

What then is a valid index of air pollution that the epidemiologist may employ in his study of health effects?

How valid are the air pollution data that the epidemiologist has at his command? At the outset it should be noted that pollutant measurements are often taken 15 feet above street level. If the object of the sampling network is to meet some specific need, however, then the station locations are adjusted to the particular requirements of the study. Few sampling stations have been established primarily for the purpose of gathering data for epidemiological studies. It should also be noted that the great variety of sampling and analytical techniques makes it difficult to compare or interpret air quality data collected from different sources.

Although the measurement of air pollution levels has progressed rapidly in the past few years and continuous monitoring is now possible, the air pollution levels reported in our cities are generally estimates based upon readings taken at one or two stations. We are therefore in a rather precarious position as to the significance and interpretation of the air quality readings now available. We must ask just how much of an area, both horizontally and vertically, these numbers represent. The question of chronology arises also, since in many instances the readings are not continuous.

For example, data on the levels of various air pollutants are collected in the City of New York, where we are fortunate indeed to have a growing Department of Air Pollution Control. This department has established a series of stations about the city to provide continuous information on smoke shade. Since we are dealing with a collection of morbidity and mortality statistics drawn from various sections of New York City, we are interested in ascertaining the variability of the records from these stations.

An analysis of variance was carried out for four of these stations, with the following interesting results:

1. The four stations differ significantly in their absolute levels with a P value of less than 0.001. We had of course expected variations between the stations and thought that possibly these variations between all of the stations might not prove significant, but this was not the case.

2. The two stations located at the Department of Air Pollution Control Laboratory at the 59th St. Bridge report significantly higher readings than the stations at Central Park in midtown and Brooklyn Tech High School, which is located in the borough of Brooklyn. The distances between the four stations are approximately 10 to 15 miles.

3. There is a significant difference in the smoke shade readings for different days of the month.

The purpose of our analysis was to enable us to determine whether one station might possibly be utilized to give us a representative reading for the city as a whole, or whether some mathematical manipulation might give us an index. It appears offhand that we cannot presume to use one station for such a purpose; the analysis also emphasized the question of just how much of an area each of our current stations represents.

Similar to the problem encountered in smoke shade is the preliminary comparison of the carbon monoxide readings measured in New York City. Continuous observations are made at two stations: the Department of Air Pollution Control Laboratory at 121st Street and the station at the 59th Street Bridge. The following information was obtained through a statistical analysis:

1. The absolute levels of carbon monoxide differ significantly for the two recording stations. As might be expected, the values registered at the Bridge are as much as 5 times higher than those at the laboratory.

2. The range of concentrations is much greater at the Bridge, as might be expected also, because of the proximity and density of traffic. The onset of high levels of carbon monoxide

starts earlier and the high levels last for a longer period of time at the Bridge.

In comparing these two stations we allow for the fact that the laboratory measurements are made 20 feet above street level, while those at the Bridge are recorded at the ramp near street level.

But before we can make any assumptions or simplifications in working with carbon monoxide, we must have a better picture of the distribution of this fugitive gas. What index can we use with carbon monoxide? Is it possible to measure this pollutant at some level in the lower atmosphere that may provide a reading applicable for health studies and yet be free from the undue influence of the source? These are the data we sorely need.

The question of whether carbon monoxide has any ill effects at chronic low levels has been reopened recently. European investigators are of an affirmative mind. But since our knowledge of the distribution of carbon monoxide in urban air is incomplete, it is difficult to infer the effects upon individuals. Sampling of carbon monoxide at street levels has disclosed values as high as 100 ppm, depending upon density of traffic and meteorological conditions.[2] The validity of our carbon monoxide readings must be probed further.

To this point our discussion has been concerned with the location of sampling stations. We have pointed out the lack of standardization in the collection and analysis of data. Before we can truly judge the validity of the numbers we are collecting and use them more meaningfully, we must improve and standardize the basic methods of measurement.

We find a weakness also in our knowledge concerning the interactions between pollutants in the atmosphere and the interactions between pollutants and weather elements. Observational and experimental evidence indicates that the toxic effect of carbon monoxide, a pollutant, is enhanced by higher temperature, a meteorological element. Or in reverse, the loss of biologically active ultraviolet radiation, a meteorological element, is brought about by increasing air pollution. It is also possible that the direct relationships we seek do not exist, but instead synergistic reactions between pollutants and weather may play a serious role.

A recent statistical investigation by Holland indicates that both atmospheric pollution and low temperature have an effect on acute respiratory admissions to London hospitals. In this study it was not possible to decide which had the greatest effect, the temperature or the air pollution, or the combination.[3]

The interactions of the various substances in the air must be determined in order to study more specific forms of illness. We must investigate further the role played by weather in transforming or altering pollutants in the photochemical reactions, in the absorption of gases and vapors on particulate material, and in catalytic oxidations and other chemical and physical changes.

As for the variable of meteorology itself, the effect of weather has been the subject of intensive investigation in European countries and to a much lesser degree in this country. Physiological studies have been carried out on high and low temperatures, temperature and humidity combinations, high and low barometric pressure, and other meteorological elements.

Extreme weather conditions, such as severe and prolonged heat waves, have been shown to increase mortality. This has been demonstrated for our area of interest by Kutschenreuter.[4]

Human bioclimatology is a vast and largely uncharted field. We can only hope that the forecast made by Dr. H. E. Landsberg will come true:

> "The greatest advances of climatology are destined to lie in the border field of biology, provided an adequate cooperative research program is started. The interactions between the physical changes in the atmosphere and living organisms are too great a challenge to scientific curiosity to remain in a relatively unexplored state."[5]

In this area we are again fortunate, since in New York City we have abundant data from the U. S. Weather Bureau. In or near the city we have hourly surface weather observations from four locations: Central Park, LaGuardia Field, New York International Airport, and Newark Airport. We have more data, though less detailed, from the Bureau's cooperative climatological network of about 30 stations. We even have an upper-air sounding record, from N. Y. International Airport, so we have low-level inversion data, etc.

Researchers in other areas may not be so fortunate. Most cities have only one Weather Bureau station, usually at an airport, away from the population from which the morbidity and mortality data are derived. The network of atmospheric sounding stations, adding the necessary third dimension, is much sparser than the network of surface weather observations. In short, there is a problem in the availability of the meteorological information. Beyond this, we need more research on urban microclimatology -- the variations of climate between, for example, the airport where the meteorological data come from and the various parts of the city where the people live and die. We need more research on the structure of the lower atmosphere over our cities, with respect to both turbulence and microclimatology. As Wexler has mentioned, the routine meteorological data are not suitable for short-term time and spatial studies of air pollution.[6]

But even the possession of abundant routine data poses its own problems. One of the first questions we had to settle in our study was whether we might use the meteorological observations from one station to correlate with the mortality data for the city as a whole. We were dealing with a population of 8 million in an area of 365 square miles. The residents are living in environments ranging from semi-suburbs to stone canyons, in a climate where, for example, sea breezes may be cooling Staten Island, Lower Manhattan, and southern Brooklyn and Queens, while the residents of the Bronx, Upper Manhattan, and the rest of Queens and Brooklyn are sweltering in the heat.

With the assistance of the Weather Bureau's National Weather Record Center, we compared a year's series of hourly temperature, pressure, humidity, and wind observations from the four locations previously mentioned, plus Battery Place, the former site of the Weather Bureau City Office. We found that the data from the five stations vary significantly with regard to absolute values, but that with regard to changes in the values the differences were not meteorologically important. In short, there was a spatial but not a chronological difference. This result was satisfactory, since it was the frequency and magnitude of the weather changes that we felt all along represented the best key to the interpretation of the mortality data. There is too much uncertainty about the applicability of the values of the elements to do much with the absolute values except in terms of large departures from "normal."

While our experience has been confined to New York City data, we believe that the same needs apply elsewhere, not only in urban areas but in rural as well. Therefore, before summarizing the foregoing in the form of conclusions as to present and future needs for meteorological and air quality observations, we must consider the important phase of rural investigations that we have so far not mentioned. These needs are just as important as those we have cited for cities. Much of what we have said applies to rural areas, so we need not repeat ourselves. We do want to bring out a few important points.

The first is the comparative lack of knowledge about rural environments as regards the atmospheric, the air pollution, and the medical information required. Weather Bureau stations are near or in the population centers; except for military airfields, climatological information in the rural areas is limited to the temperature and precipitation reports of the Weather Bureau's cooperative observers. The stations of the solar radiation observation network are mainly in urban areas. There is a need for more observations of solar radiation, surface winds, and low-level inversions from the rural areas. There is an equal need for more air quality observations from such areas. And, just as the morbidity and mortality data for our cities need to be improved and systematized, so do the same data for non-urban locations.

There are several factors that support the foregoing statements in terms of the needs of human bioclimatology. First, we should have some idea of the ordinary air pollution levels away from the major sources, in order to find out what our supposedly healthier country cousins are breathing and to compare their medical histories with those of us who gasp in the big cities.

Secondly, before we can decide how urban climates modify air pollution and how air pollution modifies urban climates, we should know more about non-urban climates and microclimates. For example, how are we to compare New Yorkers with the Westchester suburbanites and the Suffolk County farmers?

Thirdly, we know that reduction of solar radiation is an important health aspect of city climate and air pollution; and we know that solar radiation itself is a major factor in certain forms of morbidity.

Finally, we know that agricultural research specialists are becoming increasingly concerned about the effects of air pollution on plants and animals. We know, too, that agricultural meteorology and agricultural climatology are experiencing a renaissance in many sections of our country, thanks to the cooperation of the U. S. Weather Bureau and State Agricultural Experiment Stations.

We suggest that we need the help of the agricultural interests, and they need ours. For example, in the Midwest a network of Model Agricultural Weather Stations has been proposed. and some have been established. Shouldn't these include air quality observations? Also, shouldn't more meteorological stations everywhere have air sampling instruments and vice versa?

Conclusions:

The following are the conclusions at which we have arrived:

1. We need better morbidity and mortality data, and more laboratory investigations, to assess the physiological meaning of our meteorological and air quality observations.

2. We need to standardize the sampling and analytical techniques for continuous air monitoring to match the rather high degree of standardization that exists in the meteorological observations.

3. We need more joint meteorological and air sampling stations in cities and towns and in rural areas.

4. We need to have these stations, primarily the rural ones, instrumented to furnish more information on surface winds, low-level atmospheric conditions, and solar radiation.

5. We need to encourage and support the U. S. Weather Bureau so that more observations of the weather and climate can be made in the places where the people live, in addition to where the airplanes take off and land.

6. We need research on the meteorological and air quality data to translate them into models for obtaining meaningful indices of air pollution that may be interpreted in terms of health, both in urban and rural areas.[7,8]

7. We need more cooperation and more teamwork from everybody -- the general public; the local, state, and federal medical, public health, meteorological and climatological, agricultural and industrial organizations -- to obtain the observations needed and to achieve the goal the Surgeon-General has defined: "To determine the conditions under which toxic substances in the community atmosphere affect human health adversely, and the measures which must be applied to prevent adverse effects."[9]

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DISCUSSION

DR. LODGE: What specifically, do you mean by measuring air pollution? Air pollution is an abstract concept. You can't measure everything in the air. This is some thousands of substances.

DR. FIELD: Well, let us put it this way, then; there are many air pollutants. We are interested in a certain number of pollutants. Let's take, for example, carbon monoxide. We are interested in the effects upon health. We feel that air pollution, while it may change the weather pattern, may bring the temperature up in our cities, may increase rainfall. All these are excellent research projects which we highly subscribe to, but what we are interested in is trying to learn what happens to a population such as that of New York City, when the amount of sulfur dioxide in the atmosphere rises to a certain level. What is the effect on respiratory disease? Does this in any way affect morbidity? Does this in any way hospitalize people?

What we require are more adequate measures of sulfur dioxide that will tell us what these readings do mean in terms of area and population effects. Right now we are at a loss. We have five or six stations that we compare and we find that they vary greatly. Since we would like to compare any change in specific pollutants as they are measured now, carbon monoxide, sulfur dioxide, etc., we would like to know just how much of an area these pollutants actually embrace, what mortality and morbidity data must we confine ourselves to. For example, it has been mentioned that stagnation, large high-pressure systems moving into an area, will create certain stability, inversions, and all the weak wind patterns that go along with this, and that this would increase air pollution.

Well, taking our cue from such a meteorological incident, which occurred in New York City in 1953, we went back into the records and studied the mortality during this period of air pollution and compared it to similar periods during 3 years prior and 3 years subsequent to the incident. At that time the only pollution data we had as a measure were smoke shade and sulfur dioxide collected at one station. Despite the fact that this was a gross air pollution estimate, we were able to define a striking increase, which proved to be statistically significant in the number of deaths in New York City.

DR. LODGE: In a more precise study, though, do you feel that you will uniquely characterize sulfur dioxide intoxication by a knowledge of sulfur dioxide pollution?

DR. FIELD: Yes, I would say so. There are different ways of grading the effects on human physiology of these various pollutants. This would be more of a laboratory type of approach.

I had mentioned to Dr. Landsberg that the Russians, for example, in setting up maximum permissible levels, will test an individual through visual stimuli. They will seat an individual in a chamber, subject him to certain stimulus of light or other stimuli, and introduce at the same time an amount of gaseous material into the room at extremely low levels. They keep testing on this basis until they find out at what level these various increments, these various changes take place. Then they will remove the initial visual stimulus, after the subject has been conditioned and introduce the secondary effect at lower and lower levels and find the threshold where he no longer feels or elicits a response. There are various ways of grading this.

Now, we feel that respiratory disease and sulfur dioxide go hand in hand. We would like very much to be able to correlate the two, but when we find that the measurements are made completely differently from city to city and techniques vary so greatly, that the measurements are made at stations which are arbitrarily set up at certain areas, without any regard to representation, I don't feel that such pollution data are adequate for our use. I was curious when I asked the question before about the oxide, whether somebody actually went out and did some surveys and then decided this was a fairly representative area, unaffected by local sources that would contribute in any way to the change.

After all, we are dealing with the numbers that you provide us for health studies and these numbers at this point are not satisfactory for our purpose.

MR. STERN: I would like to commend to Dr. Field the series of papers discussing sampling station density and placement, as a result of the Nashville study. There the city was literally saturated with sampling points in order to determine the necessary number and location of sampling points. And I think the Nashville data in the series of papers that have been published go a long way to answer some of the questions you have raised as to the meaning of any one station with relation to others in a network, and how many are needed to characterize it.

DR. FIELD: Thank you.

MR. WOHLERS: I have a simple question. So far as analytic techniques are concerned, they are physical measurements and if you want analyses at this and that location, we can provide them for you. But then, after you get these data how do you then judge whether my liver was affected or my lungs, or which has affected my head?

DR. FIELD: It has been mentioned previously that Mr. Halitsky and another health study group were entering into a study in New York City on welfare patients and the possible effects of air pollution. I have been at one or two of the meetings and I understand they have quite a problem there in trying to assay that. However, there are certain diseases we may go into and see whether we can correlate with any of the particular pollutants. For example, one of the interesting things would be to be able to compare cities. Does New York have more air pollution than Boston? I don't know whether this is possible. Is there some level that we might get, or background level of air pollution that would enable us to compare the morbidity and mortality and air pollution among cities. This has been tried in many other ways through fuel consumption and economic indices and so on. But for the actual morbidity and mortality studies underway, are pollutants as measured today, sufficient? And I feel that they are not. I don't dispute Mr. Stern's statement. I just bring out what our experience has been, the fact that stations are set up in an area and we have no prior knowledge as to whether those stations are adversely affected by the local topography or the local instantaneous release of pollutants that might occur because of factory sites and so on. Measuring carbon monoxide at a bridge will give you a good idea of traffic. Measuring carbon monoxide one story above street level in another part of town may give you something else. But I hope it is possible through your research and through what I feel is much-required research, for you to come up with numbers for us to use more meaningfully in the morbidity and mortality studies.

If we are given more precise air pollution data to work with, which you say you can provide, I am sure we will be able to study such data and those diseases which we suspect are aggravated or brought about by air pollution and weather.

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